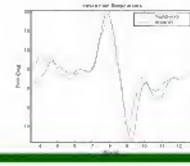


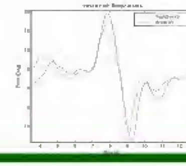
DARPA XV
List of Components and Subassemblies

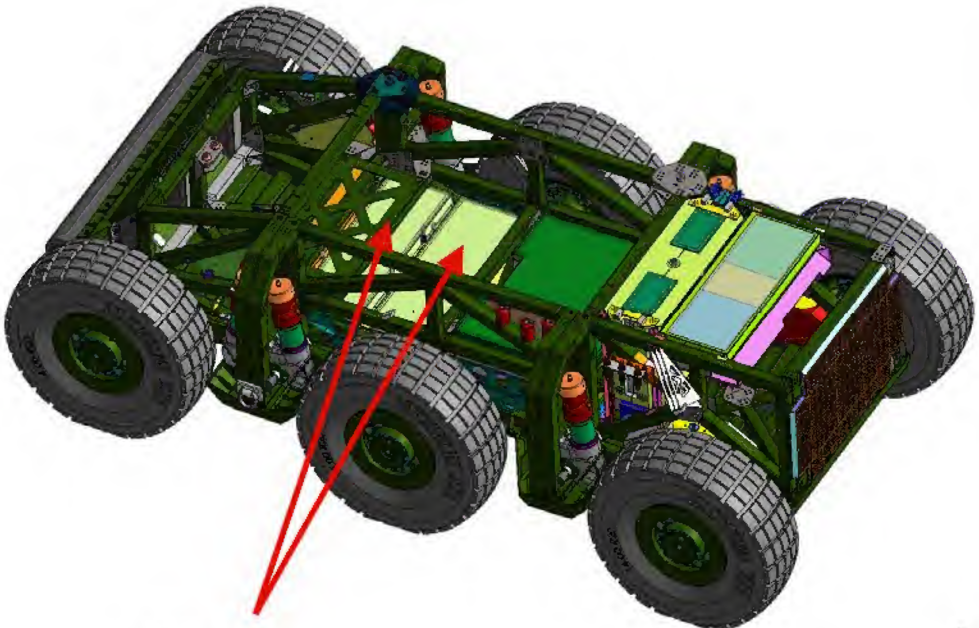
NREC Team

(b)(4); (b)(6)
[redacted]

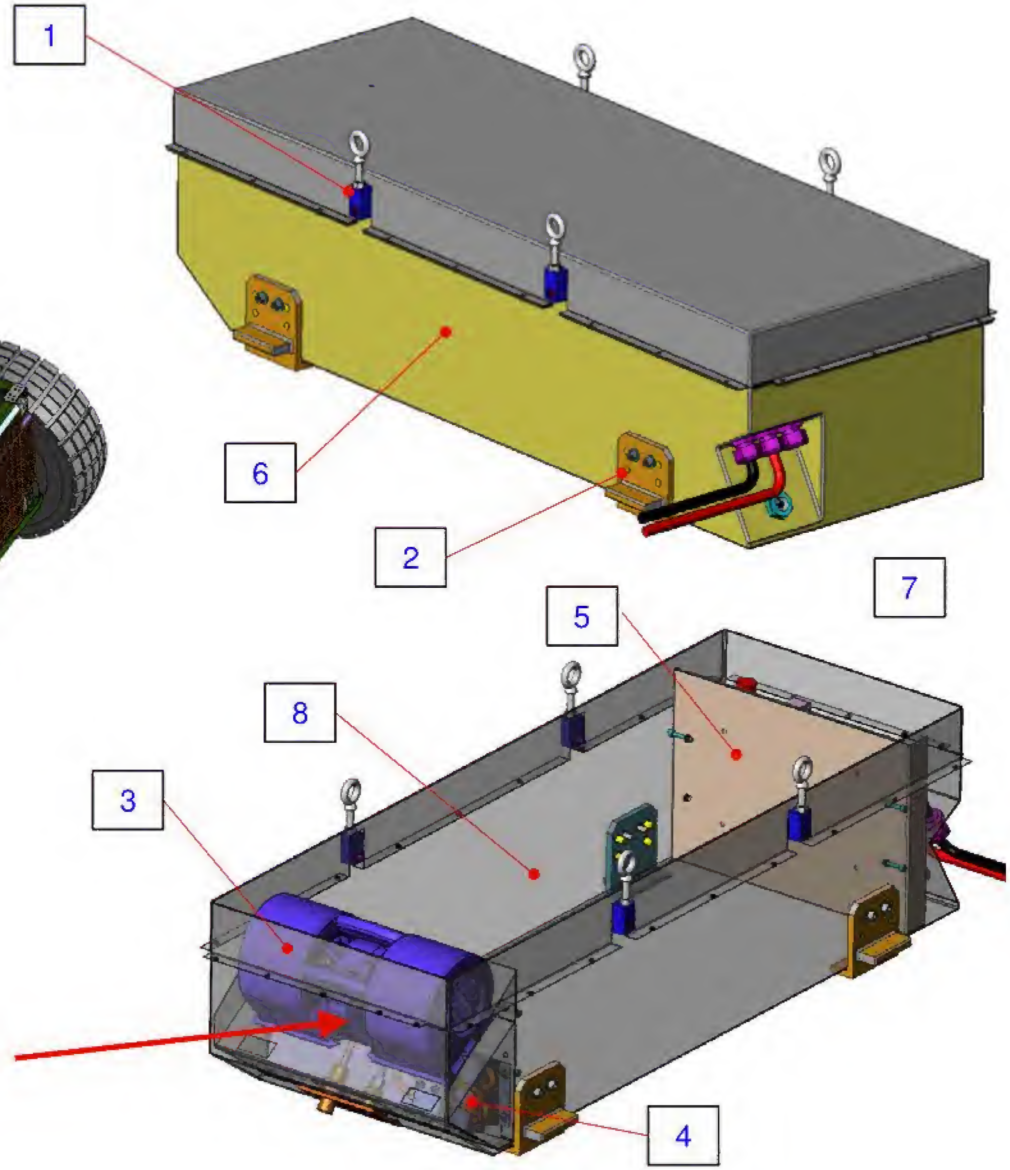
Revision 2 – November 30, 2012

Battery Frame and Cooling





Battery packs



Cooling system

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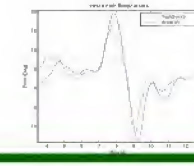
Battery Frame and Cooling System



- **Components**
  1. 4 integrated hoist points
  2. 4 mounting brackets
  3. Blower fan
  4. Tube and fin heat exchanger
  5. Electronics panel
  6. Welded aluminum housing
  7. Power cabling
  8. Internal volume for batteries
- **Description**
  - → Battery pack to power vehicle
  - → 2 packs per vehicle
    - – Vehicle is capable of operating on only 1 pack
  - → Typical current draw: 200A @ 350VDC
    - – Occasional draws at 400A
  - → OEM battery controller mounted with electronics panel
  - → Cooling
    - – Forced convection w/ refrigerant system
    - – Air circulated within pack (like refrigerator)
    - – Expansion valve and evaporator inside pack
    - – Condenser external to pack
    - – Removed heat load of 200W

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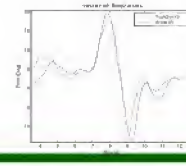
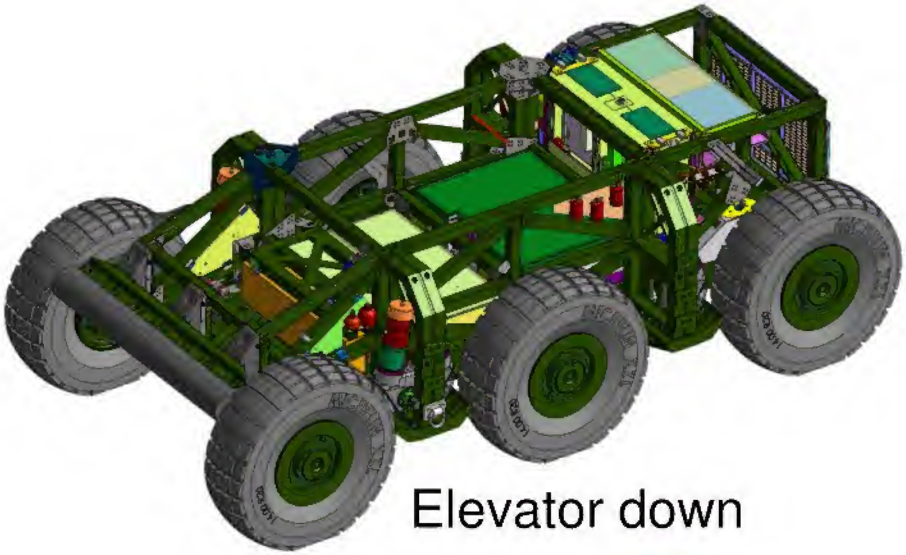
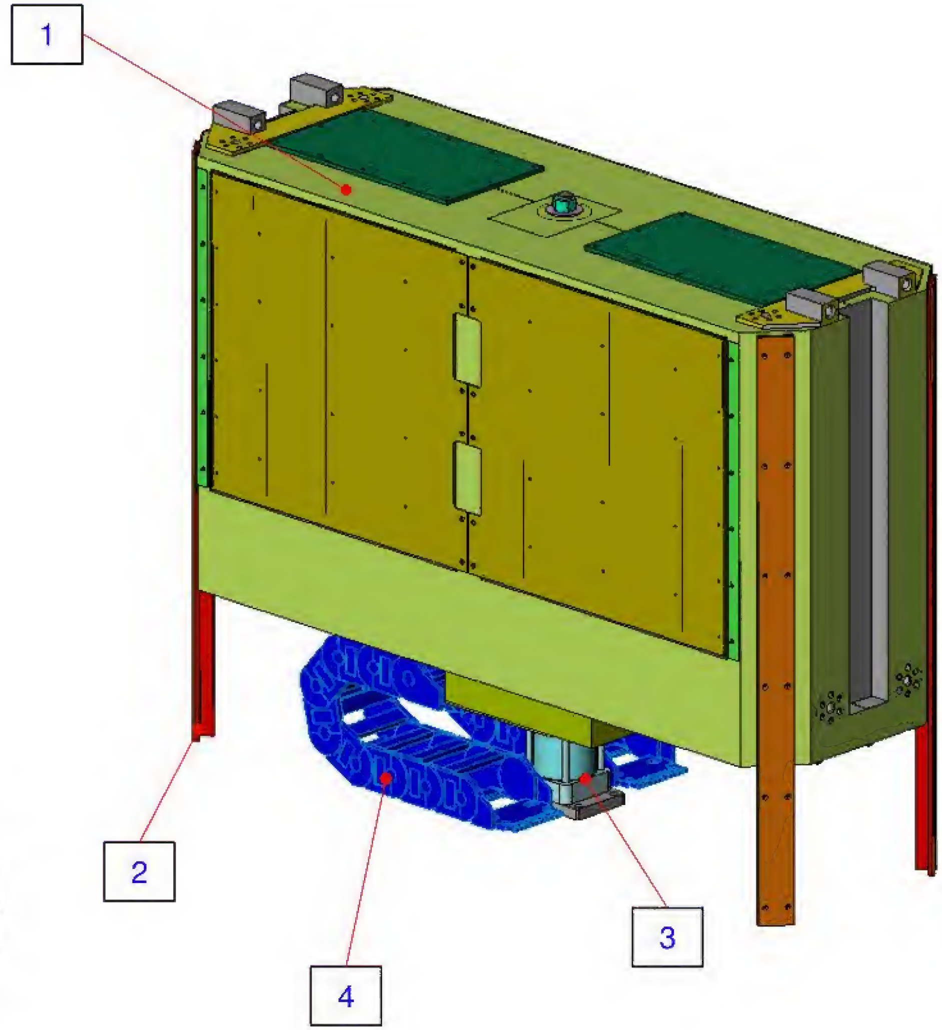
Elevator Assembly





Elevator down

Elevator up



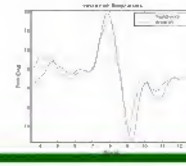
Internal components

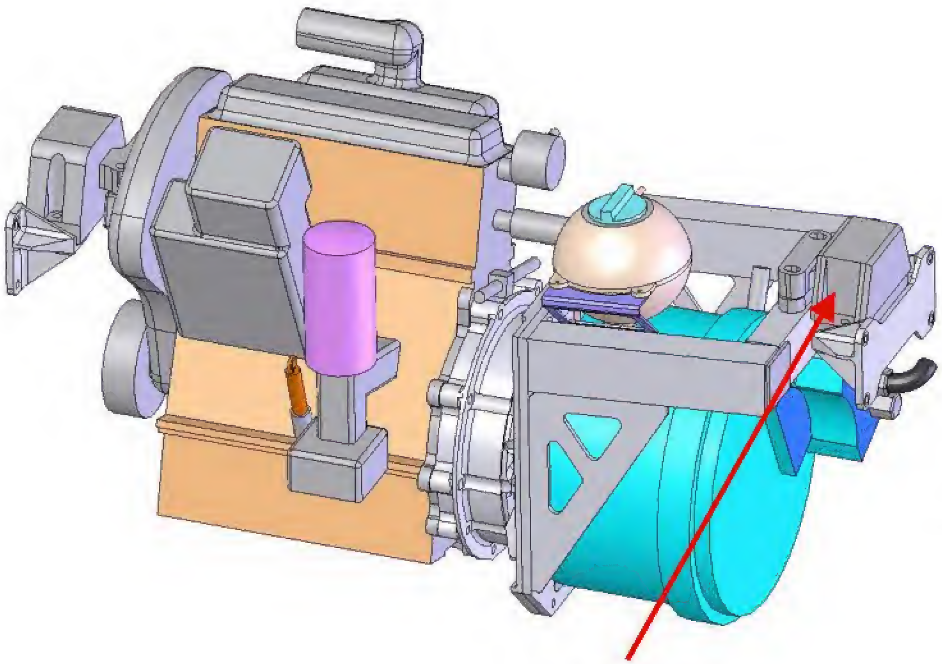
Elevator Assembly

- **Components**
  1. Aluminum enclosure
  2. Guide rails for linear positioning
  3. Pneumatic cylinder
  4. Cable management

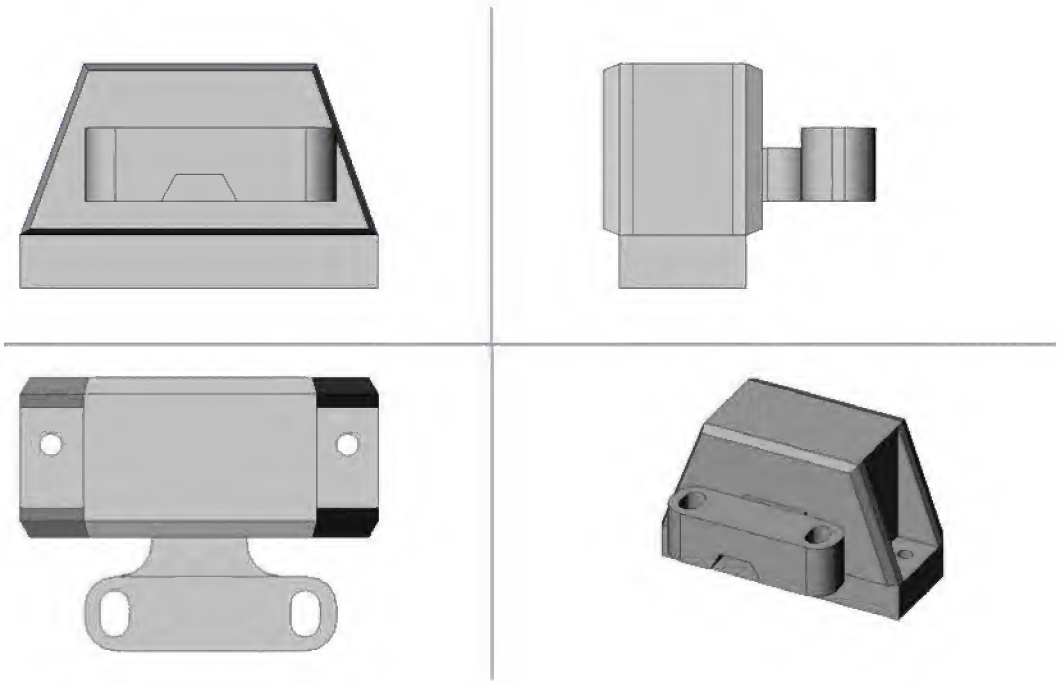
- **Description**
  → Contains high & low voltage power and control electronics, rises out of vehicle for accessibility and maintenance

Power Pack Isolation

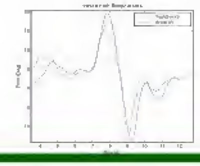




Isolation
mount

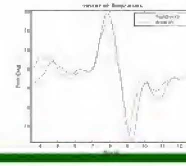


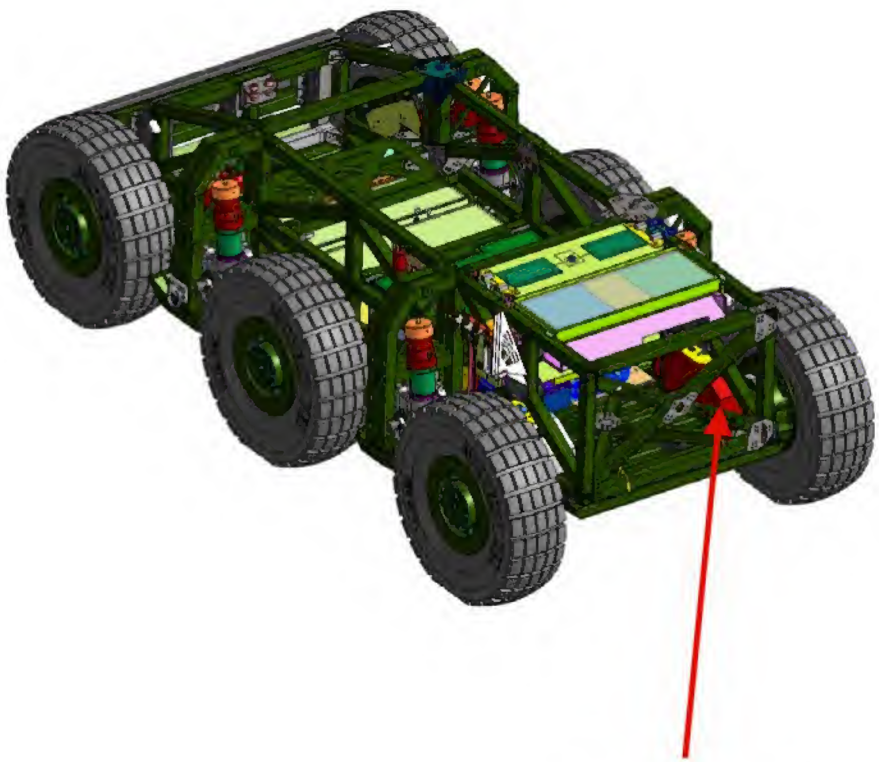
Power Pack Isolation

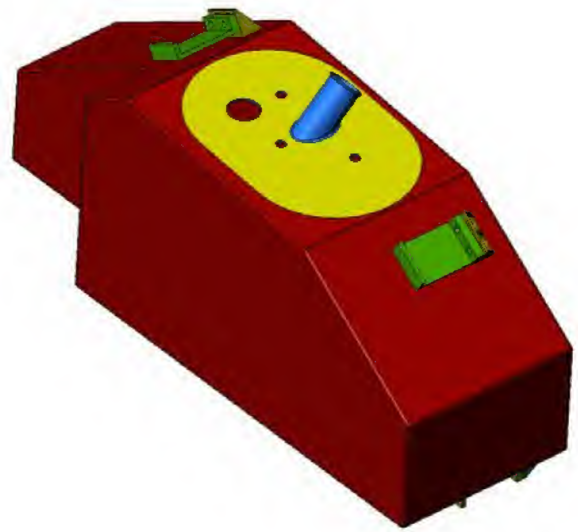


- Natural rubber and steel construction
- Weight 7.5 lb ea
- Load range 1300lb per
- Attenuation – 12.5-10,000 hz
- Transmissibility – 7hz

Fuel tank

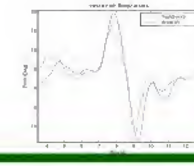






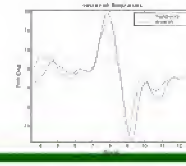
Fuel tank

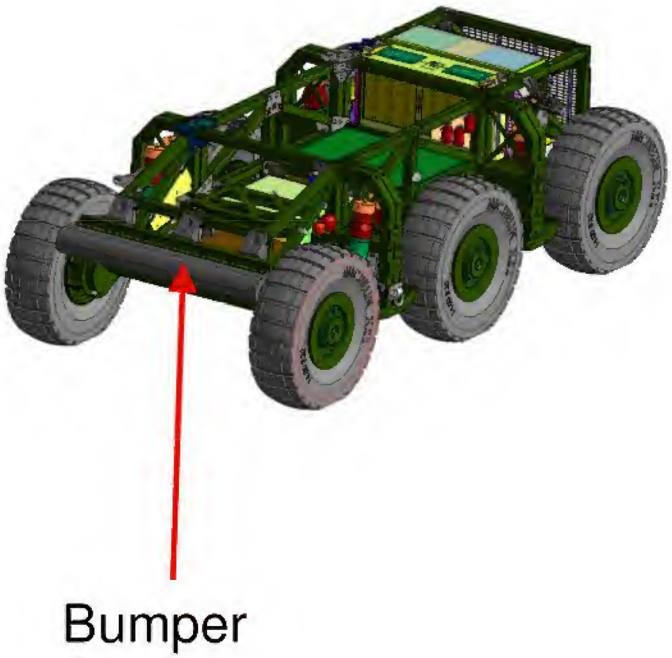
Fuel Tank

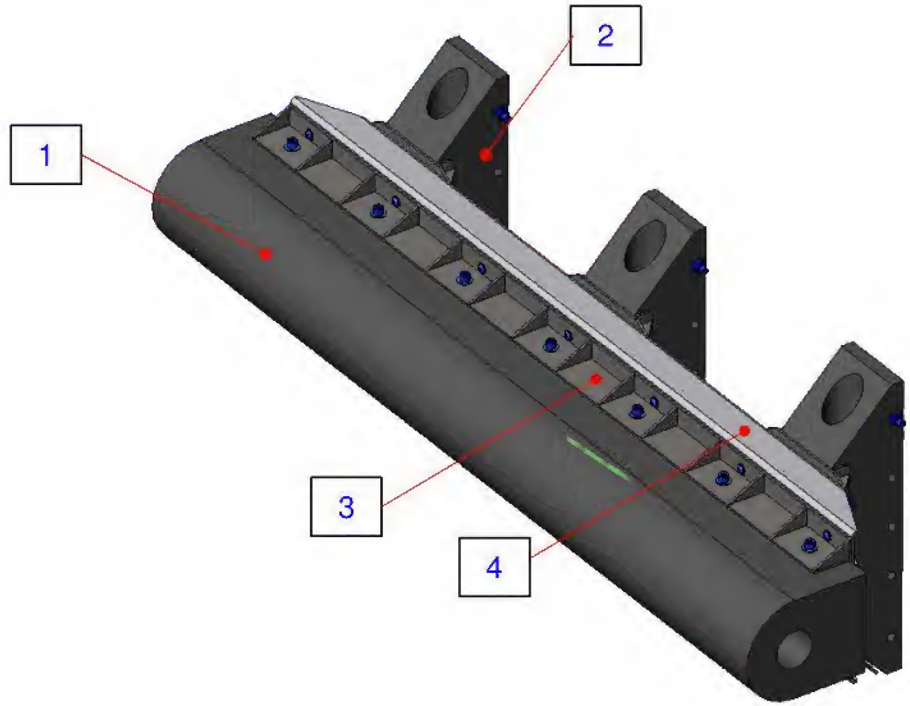


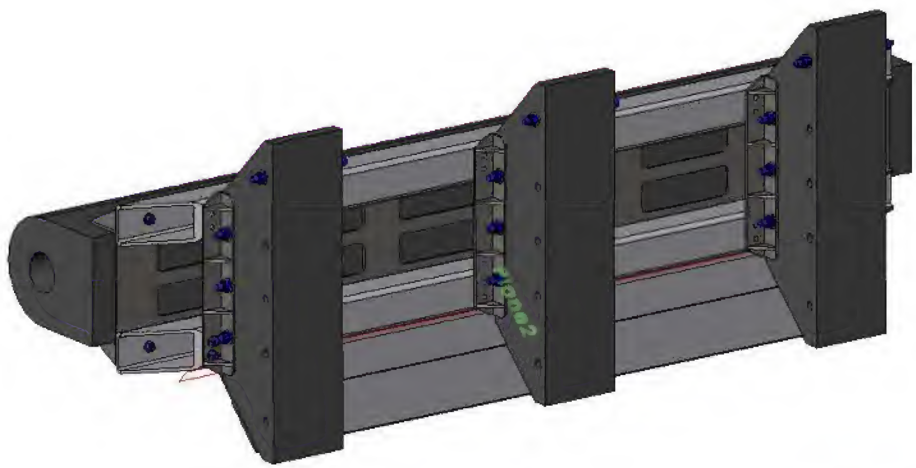
- See document DARPA-XV-Crusher-Model2-Nov2012
- Fuel cell manufactured by ATL

Two stage bumper

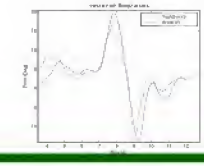








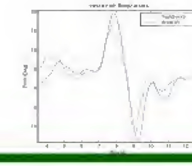
Two Stage Bumper

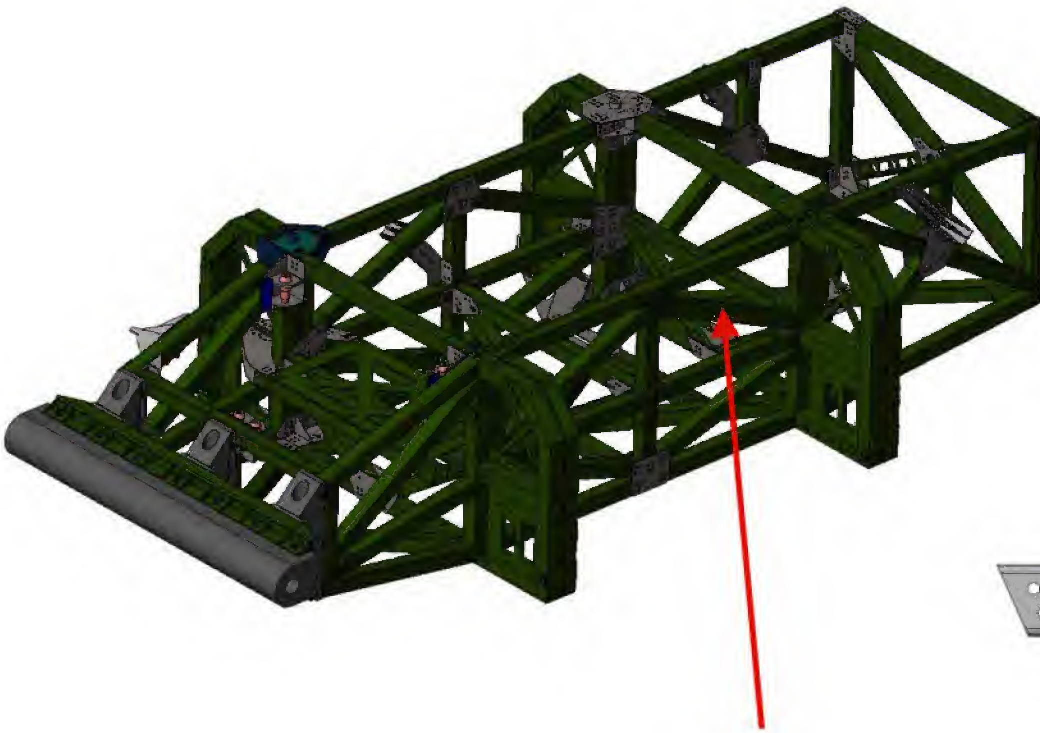


- **Components**
  1. **Compliant EPDM rubber**
  2. **Rigid EPDM rubber**
  3. **Titanium weldment**
  4. **Aluminum tube**

- **Description:**
  - → **Purpose of bumper: knock over small trees (25cm) at full speed**
  - → **2000N – cm spring rate**
  - → **440kN impact at 11g**

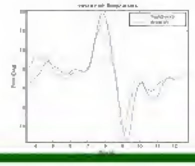
Frame Member





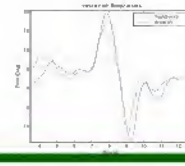
Frame
member

Frame Member

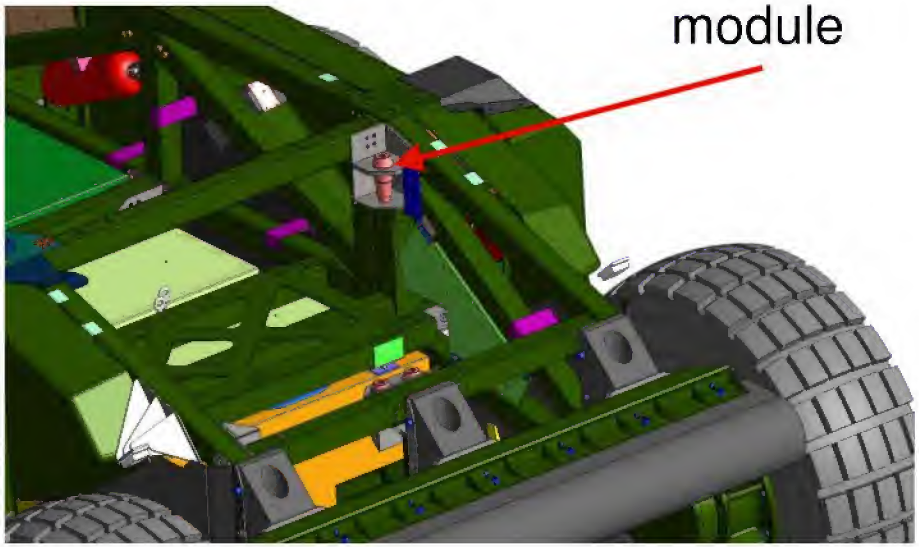


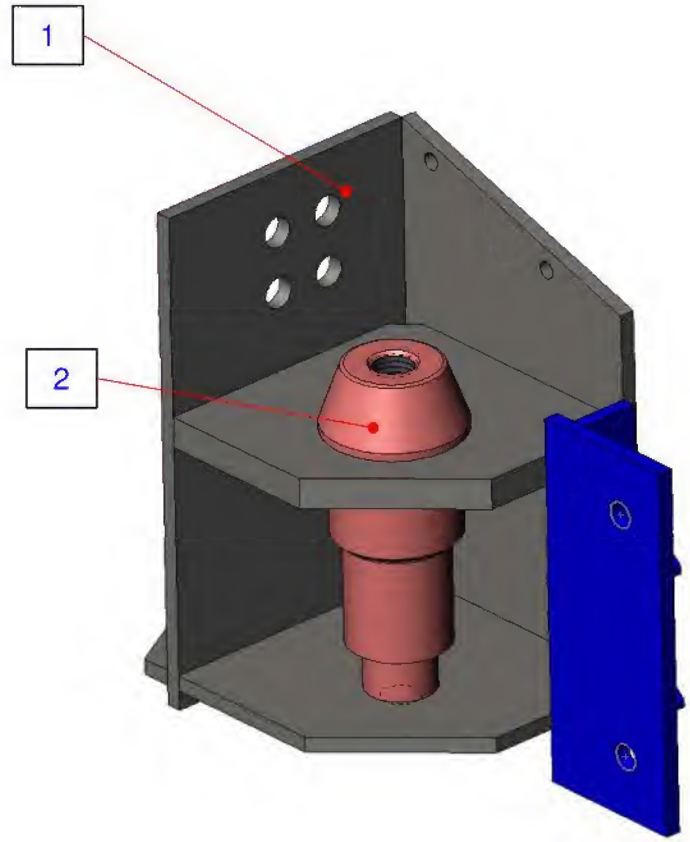
- **Aluminum 2195**
- **4 mounting holes each end**
  - → **Holes were reamed at assembly to titanium joining plates and secured with slip-fit shoulder bolts**
- **Machined (thinned in center section) for weight reduction**

Frame Capture Module

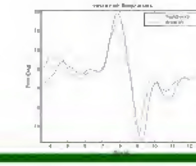


Capture module





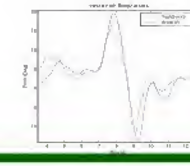
Frame Capture Module

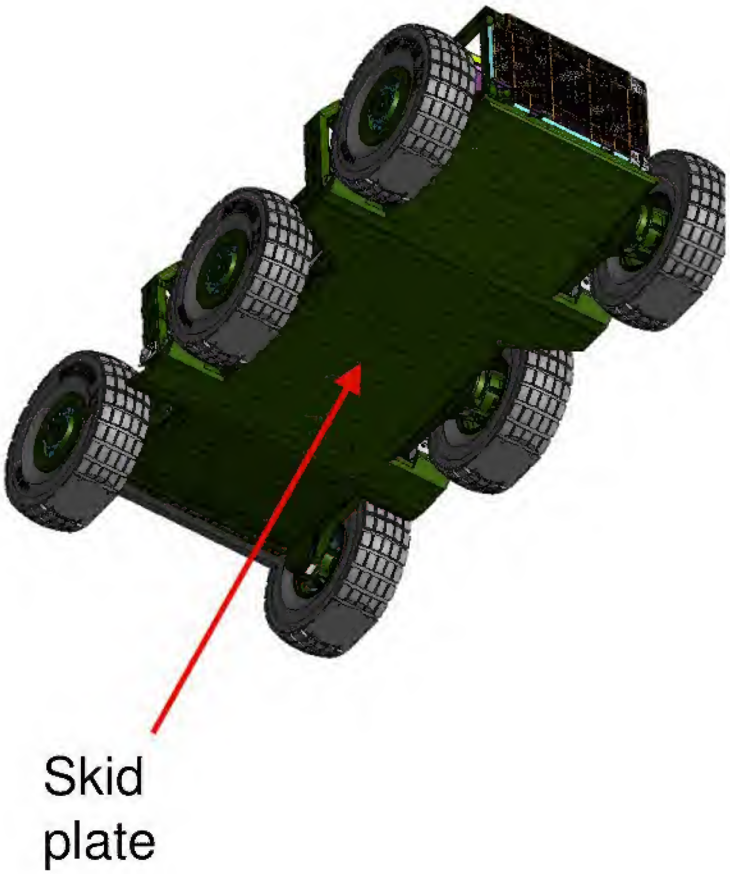


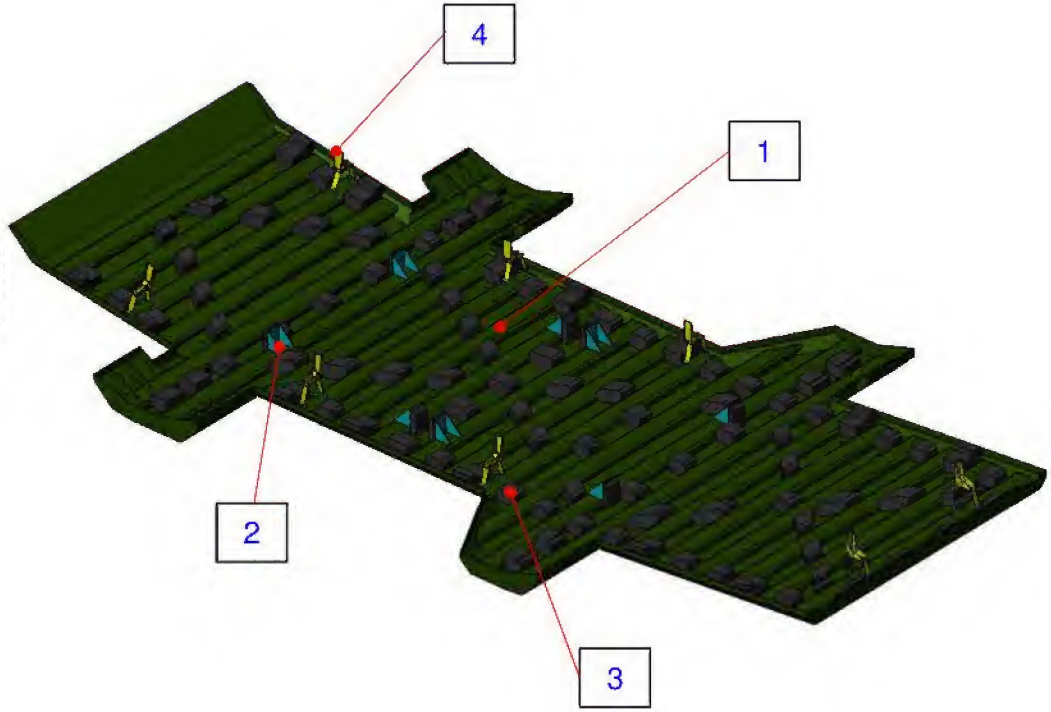
- **Components**
  1. **Titanium weldment**
  2. **4340 steel pin**

- **Description**
  - → **Mounting point for perception module**
  - → **Conical for self-alignment**

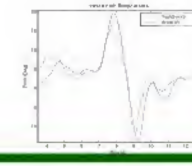
Skid Plate







Skid Plate



- **Components**
  1. **Hardox 450 steel weldment**
  2. **Longitudinal brackets (steel)**
  3. **Rubber pads**
  4. **Mounting straps (wrap around frame)**

- **Description**
  - → **Designed to protect for running over rocks**
  - → **18mm stroke (rubber compression)**

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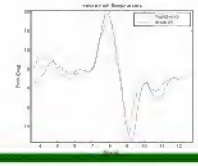
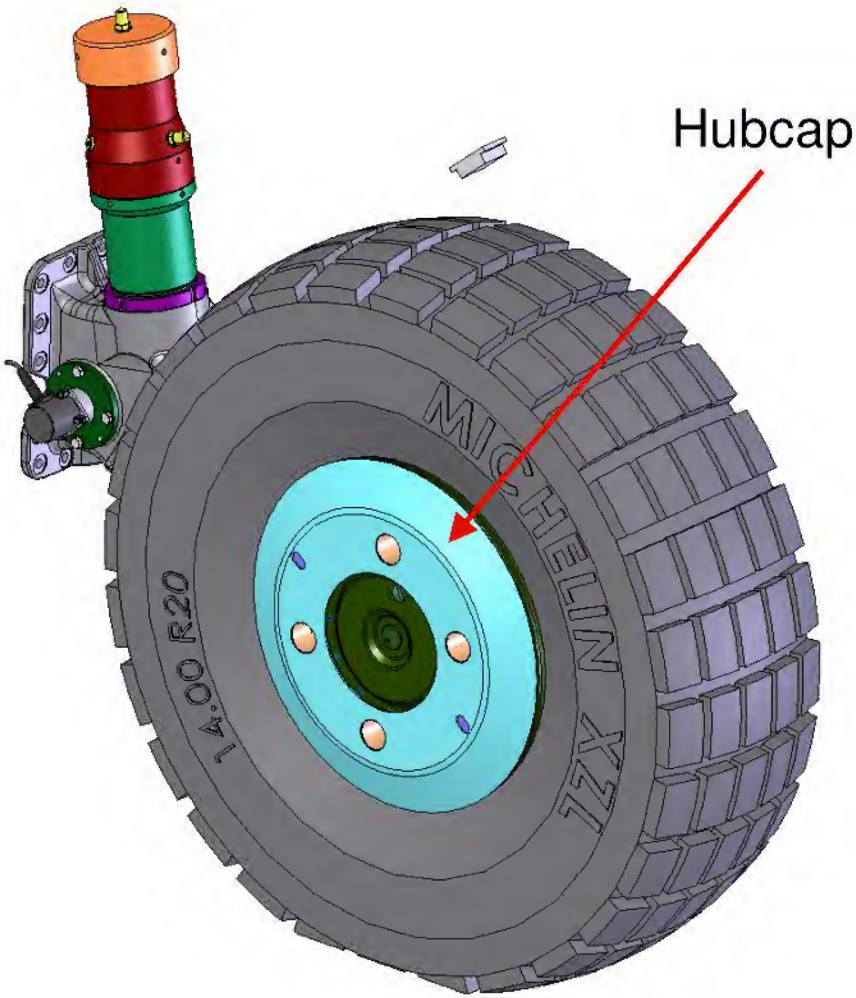
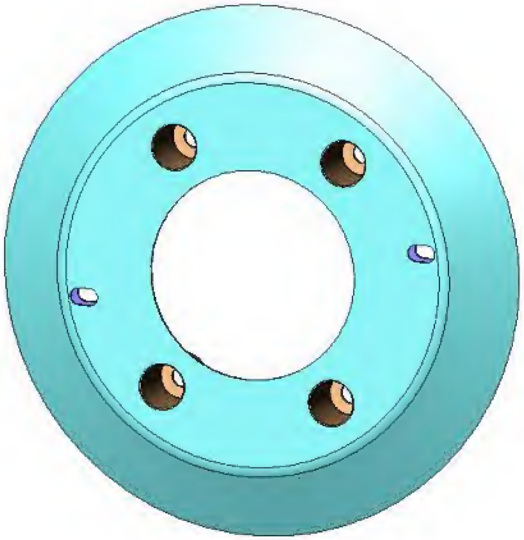
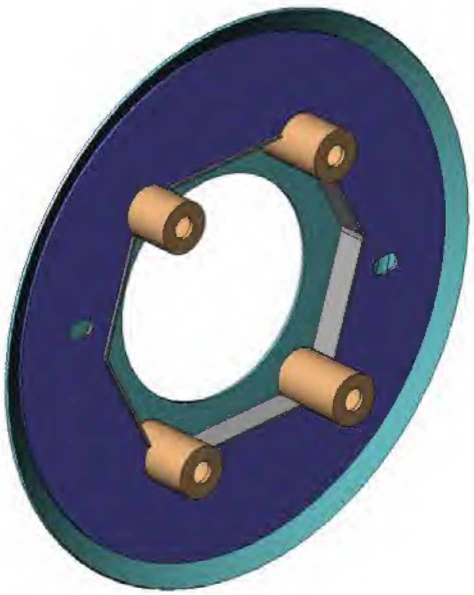
Hub Protection

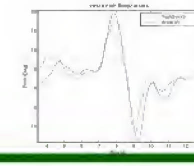






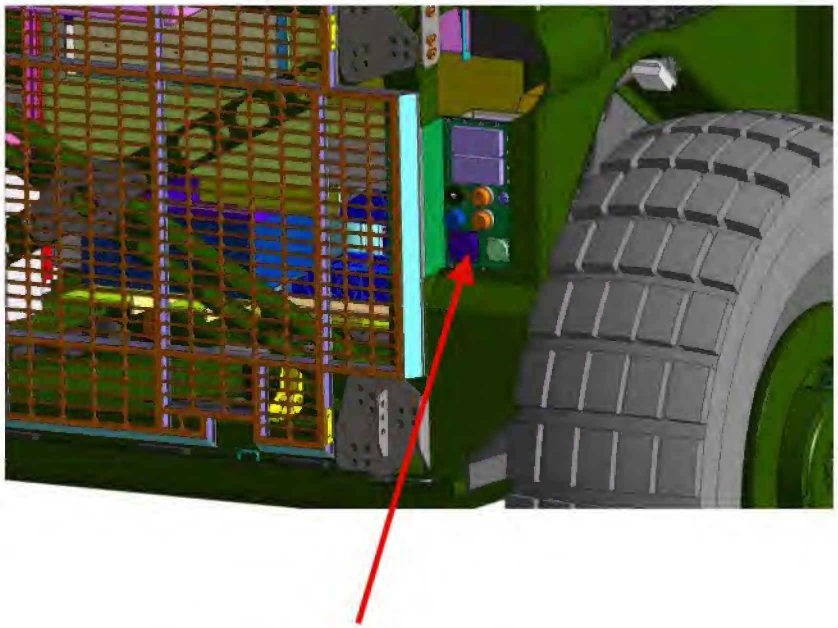


Hub Protection

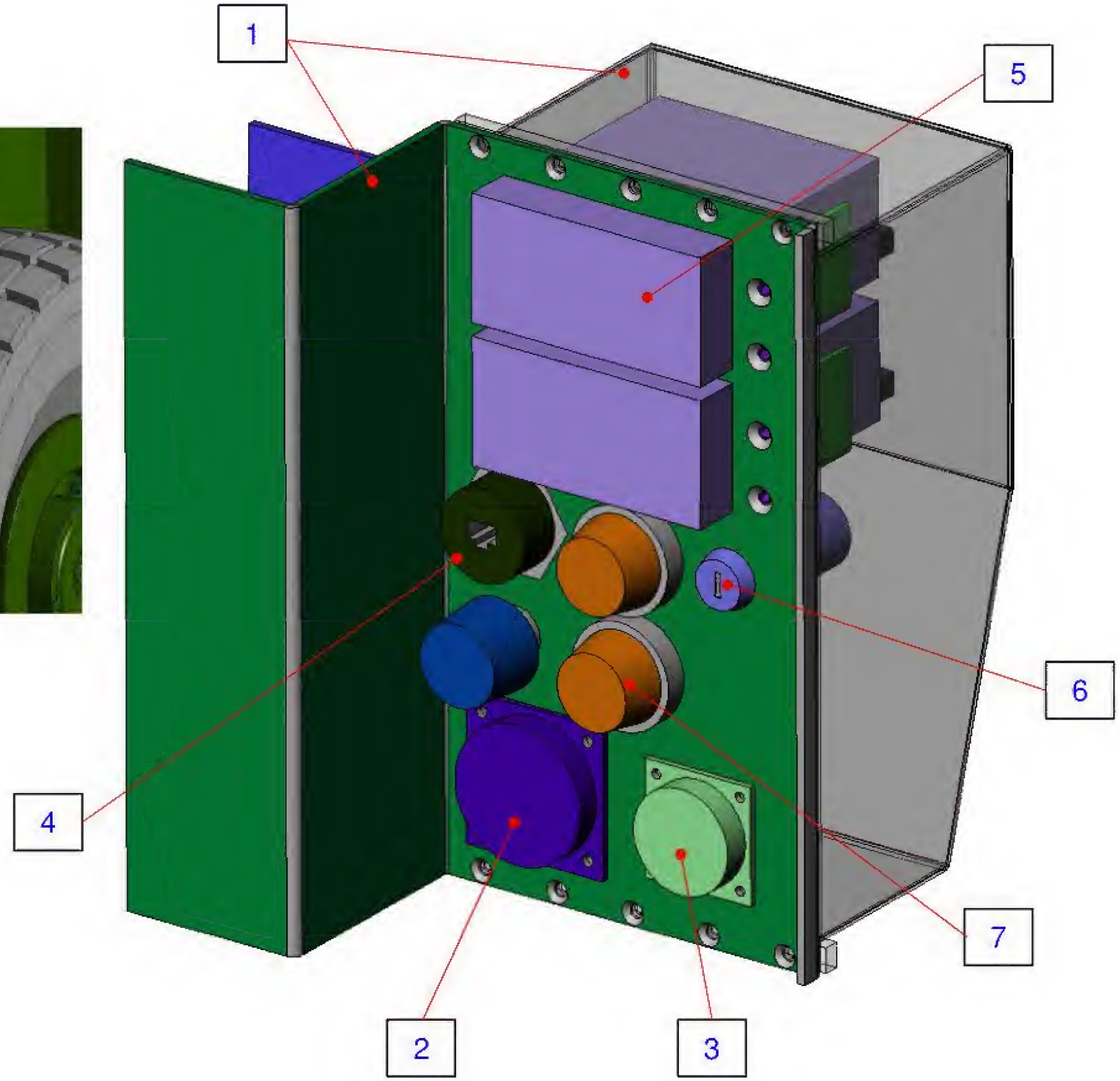


- Steel weldment
- Designed for 200kN side force from sliding into obstacle
- Protects center hub

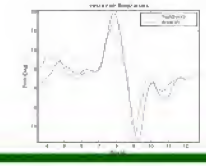
Facilities Panel



Facilities panel



Facilities Panel



- **Components**
  1. **Aluminum enclosure and mounting**
  2. **350V connector**
  3. **24V, 12V, 5V connectors**
  4. **Ethernet port**
  5. **Displays**
  6. **Key switch**
  7. **Indicator lights**

- **Description**
  - → **Interface for charging, data interface, and vehicle startup**

Hydro Strut Component Documentation

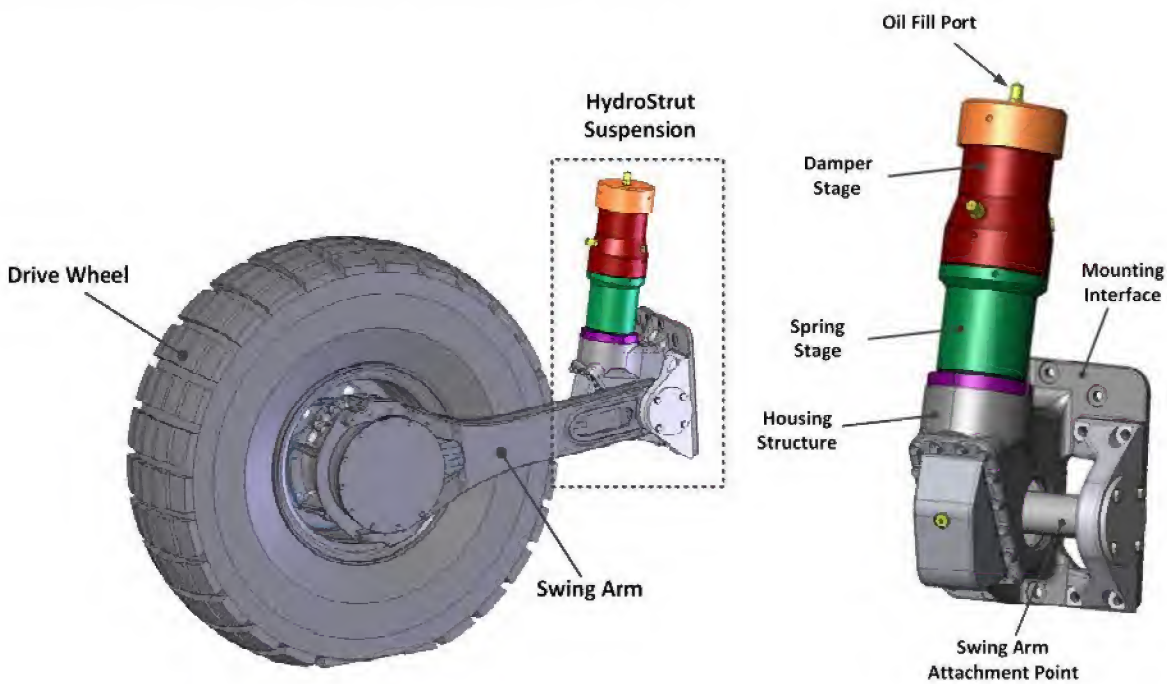
[redacted]

National Robotics Engineering Center

[redacted]

Overview

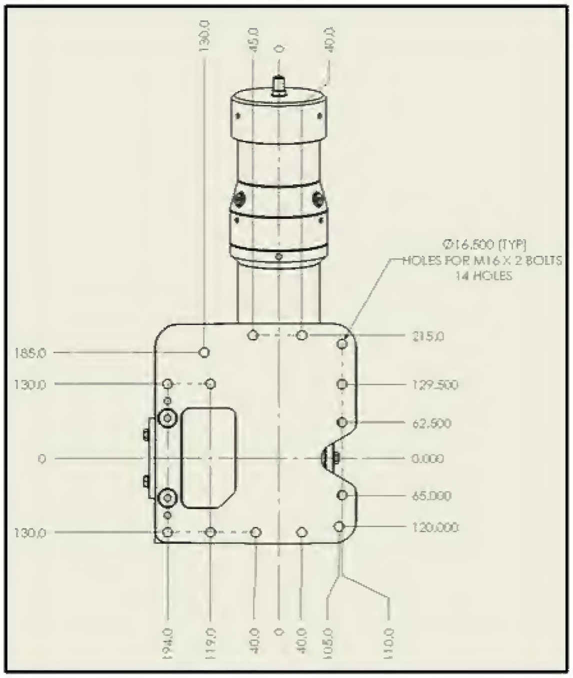
This document gives the physical and dynamic properties for the hydro strut suspension component used in the Crusher vehicle. The goal of this document is to provide enough information for the component to be integrated into the AVM component library.

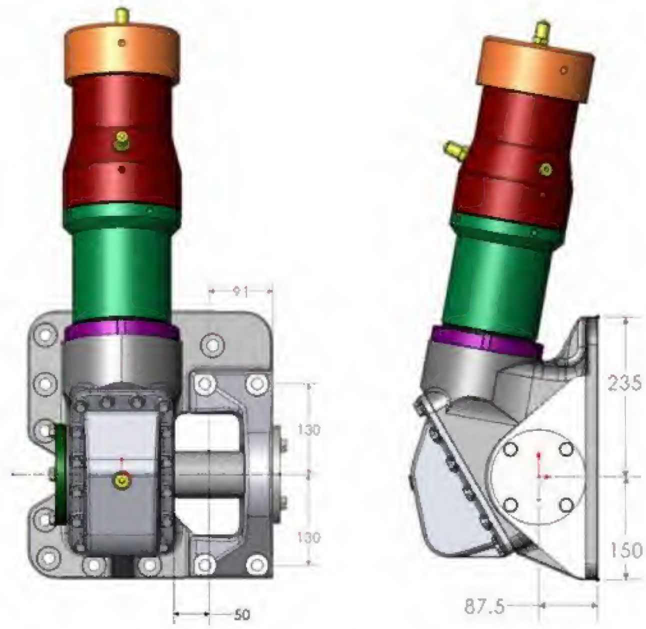


In the system diagram above, the hydro strut suspension component is used to connect to the swing arm component of a drivetrain, which is subsequently connected to the drive wheel. For this analysis, the hydro strut suspension component is separated from the rest of the drivetrain. Its physical and dynamic properties are given so that it can be characterized on its own so that it can easily be integrated into system design.

Physical Properties

The hydro strut is made of several major subcomponents. The swing arm assembly connects to the hydro strut assembly via the swing arm attachment point (2 5/8" diameter steel shaft). That shaft then acts on several internal components that provide spring and dampening force as the axle rotates. The component is mounted onto an assembly via several bolts on the rear side of the mounting interface.





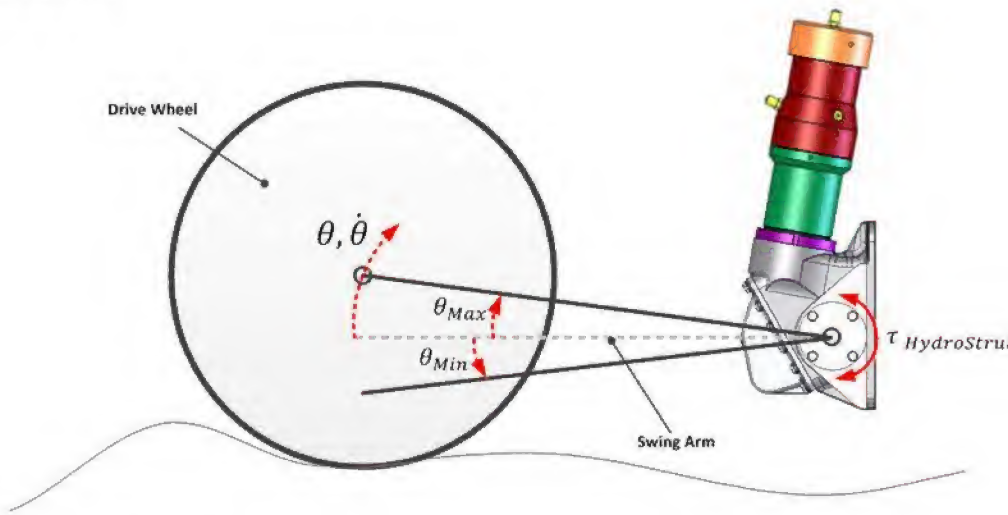
These holes are 16.5 mm bore diameter to allow for the installation of 16mm diameter bolts, with their locations described in the picture above (to the left). Additionally, the location of the shaft where the swing arm mounts is described in the picture above (to the right). The layout of the bolt-hole pattern and shaft location are shown with dimensions in mm.

The mounting interface and hydro strut structure was built out of several cast carbon steel components that are assembled together. It can be assumed that the mechanical properties for the load bearing members of the component to follow the data in the table below:

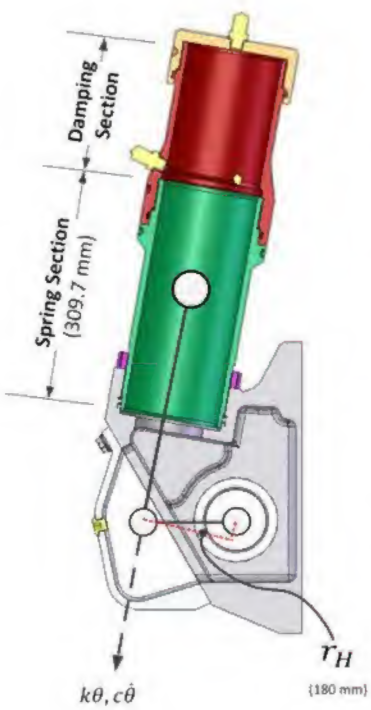
Elastic Modulus	2.00E+11	N/m^2
Poissons Ratio	0.32	N/A
Shear Modulus	7.60E+10	N/m^2
Density	7800	kg/m^3
Tensile Strength	4.83E+08	N/m^2
Compressive Strength in X		N/m^2
Yield Strength	2.48E+08	N/m^2
Thermal Expansion Coefficient	1.20E-05	/K
Thermal Conductivity	30	W/(m·K)
Specific Heat	500	J/(kg·K)
Material Damping Ratio		N/A

The hydro strut component assembly model is simplified and does not contain many internal components (bearings, linkages, *etc.*). The overall weight of the full component that would be integrated can be assumed to be 50 kg.

System Dynamics



When integrated into a drivetrain suspension, the hydro strut component will provide resistive loads onto the swing arm as it reacts against changing road / ground conditions. The swing arm is able to move radially about the swing arm attachment point of the hydro strut. It can be assumed that the natural "zero" position of the swing arm is parallel to level ground. The swing arm is able to move radially to a maximum and minimum angle ($\theta_{Max}, \theta_{Min}$). For the example component, $\theta_{Max} = 25.2$ °and $\theta_{Min} = -25.2$ °

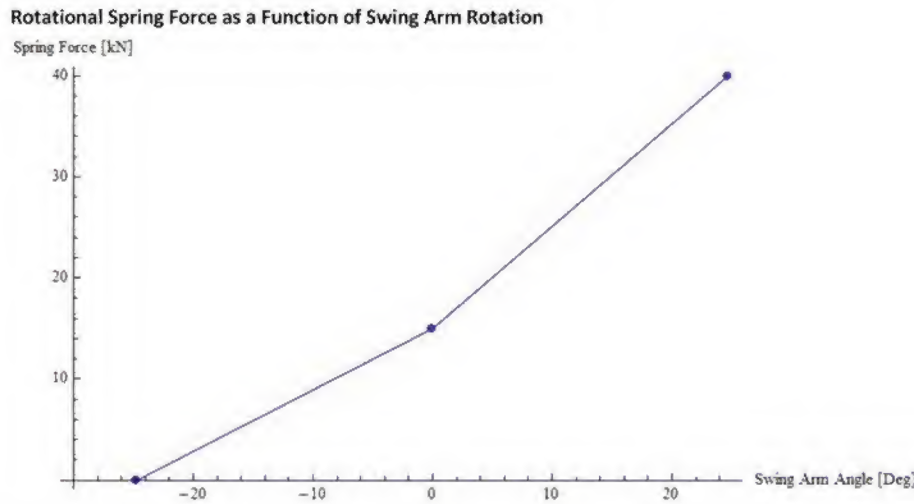


As the swing arm rotates, it causes the shaft within the hydro strut to rotate at the same rate. Internal to the component, a linkage system connects a linear spring and damper system to the swing arm connection shaft (as shown in the image to the left). The linear spring and damping forces are then translated into a reactive torque load about the swing arm connection shaft due to the linkage offset, r_H. For this assembly, the value of r_H is 180 mm.

The spring force for the hydro strut has two distinct linear values depending on the rotation of the swing arm. Due to the nature of the linear spring and the preload in the system, the linear spring force is estimated to be

$$F_k = \begin{Bmatrix} 0.6073\,\theta + 15 & \theta \leq 0 \\ 1.0122\,\theta + 15 & \theta > 0 \end{Bmatrix} \text{[kN]}$$

The spring force can also be described in the following graph.

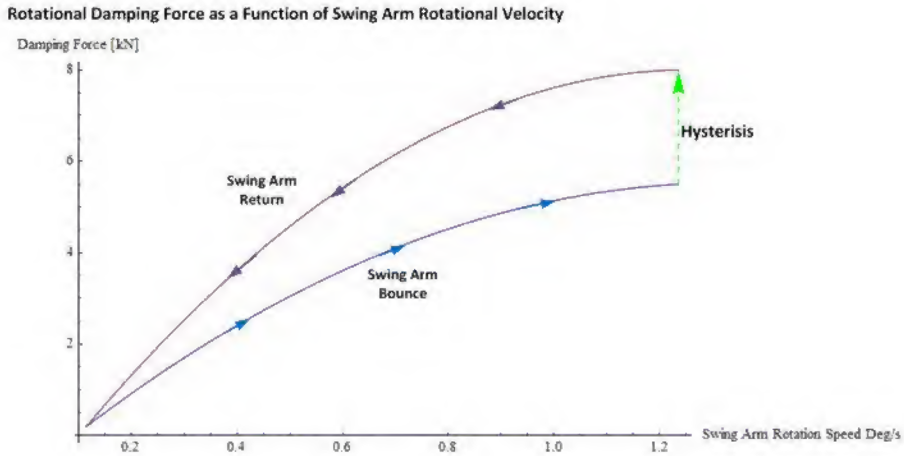


The damping force for the component depends on the direction of the angular velocity of the swing arm.
Positive angular velocity refers to "swing arm bounce" motion whereas negative angular refers to "swing arm return". The relationship between angular velocity and damping force is estimated (using a 2nd order polynomial fit) to be

$$F_c = \begin{Bmatrix} -3.622\,\dot{\theta}^2 + 9.617\,\dot{\theta} - 0.853 & Bounce \\ -5.991\,\dot{\theta}^2 + 15.044\,\dot{\theta} - 1.443 & Rebound \end{Bmatrix} \text{[kN]}$$

It is important to note that the magnitude of the angular velocity is used to estimate the damping force and the sign of the velocity only determines the mode in which it is operating. Also, there is a noticeable amount of hysteresis during operation between the bounce and return modes of the damper.

The damping force can also be described in the following graph.



Using the derived values for the spring and damping force, a general relationship of the dynamic torque applied to the system from the hydro strut component can be described as

$$\tau_{Hydrostrut} = (F_k + F_c)\, r_H$$

System Variability

The hydro strut component can be adjusted to accommodate different angular ranges of motion as well as varying spring and damper rates. The spring section of the hydro strut component can be elongated or shortened to change the range of motion of the swing arm. With the component model used ($\theta_{Max} = 25.2\ °$ and $\theta_{Min} = -25.2\ °$) in this analysis, the spring section has a total length of 309.7 mm. Of that length, 169.4 mm is taken up in the linear motion of internal elements leaving 140.3 mm in supplementary support structure. A generalized relationship can be derived that gives the adjusted spring section length based on varying θ_{Max} and θ_{Min} as shown below. Note that angles are in degrees and lengths are in mm.

$$L_{SpringSection} = (\tan|\theta_{Max}| + \tan|\theta_{Min}|)\ x\ 180 + 140.3 \quad \text{(mm)}$$

The other factors that can be adjusted in the component are the spring and damping rates. This component varies the spring rate by changing internal components that does not affect the external geometry of the system. Therefore, it can be assumed that the spring and damping rates can be scaled to accommodate a wide range of options for use in drive train systems. The characteristic shapes of how the spring and dampers act in the system will not change, though.

Supplementary Materials

A STEP file of the hydro strut assembly is included with this report packet.

If there are any questions or complications, please contact:

(b)(4); (b)(6) [redacted]
Carnegie Mellon University, Robotics Institute
National Robotics Engineering Center
10 40th Street, Pittsburgh, PA 15201, USA
Tel. (b)(4); (b)(6) [redacted]

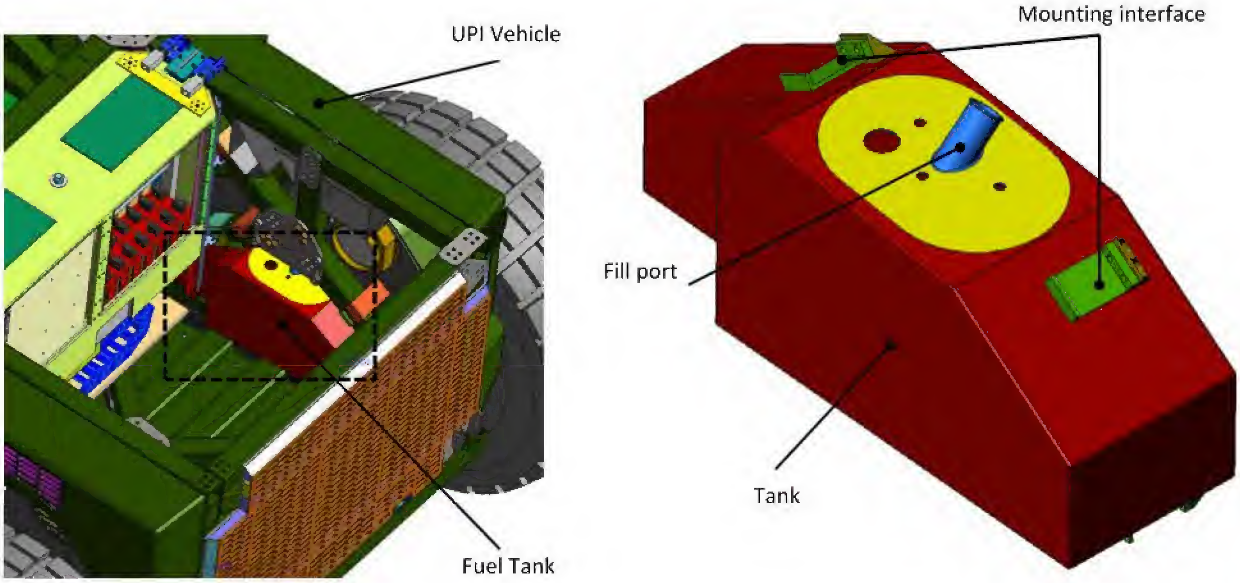
(b)(4); (b)(6) [redacted]
Carnegie Mellon University, Robotics Institute
National Robotics Engineering Center
10 40th Street, Pittsburgh, PA 15201, USA
Tel. (b)(4); (b)(6) [redacted]

Fuel Tank Documentation

(b)(4); (b)(6) [redacted]
National Robotics Engineering Center
(b)(4); (b)(6) [redacted]

Overview

This document gives the physical properties of a fuel tank component used in the Crusher vehicle. The goal of this document is to provide enough information for the component to be integrated into the AVM component library.



The fuel tank shown above supplies fuel to the vehicle power pack. For this analysis, the fuel tank is separated from the rest of the vehicle. Its physical properties are given so that it can be characterized and easily integrated into system design.

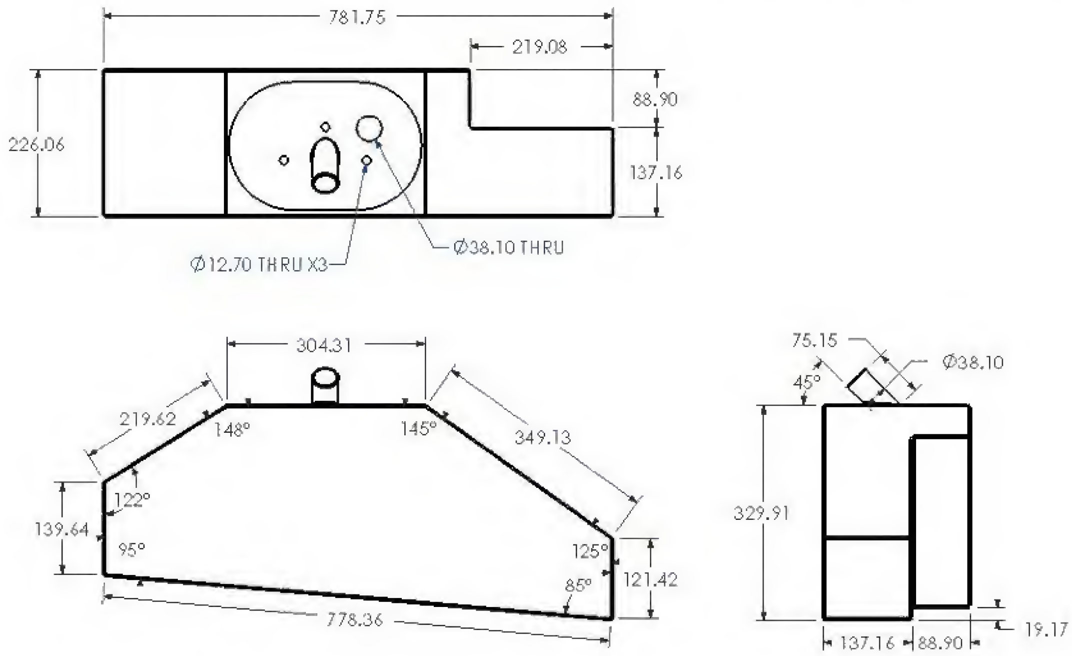
Physical Properties

The fuel tank consists of very few components. The tank is made of 1/16 inch 6061 aluminum sheet, which is fully welded at all seams to contain liquid fuel. The mounting interface consists of 6061 aluminum machined angle brackets welded to the tank, which interface with clips that mount to the vehicle frame. The clips are mounted using ¼-20 bolts.

The fill port on the top of the tank is made of aluminum and welded to the tank. There are additional ports on top of the tank for connecting fuel lines to the power pack and fuel level monitoring.

Dimensions

Dimensions of the fuel tank are shown below. The tank has a volumetric capacity of 39.3 liters.



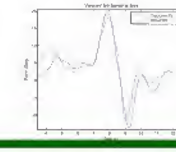
Supplementary Materials

A STEP file of the hydro strut assembly is included with this report packet.

If there are any questions or complications, please contact:

(b)(4); (b)(6) [redacted]
Carnegie Mellon University, Robotics Institute
National Robotics Engineering Center
10 40th Street, Pittsburgh, PA 15201, USA
Tel. (b)(4); (b)(6) [redacted]

(b)(4); (b)(6) [redacted]
Carnegie Mellon University, Robotics Institute
National Robotics Engineering Center
10 40th Street, Pittsburgh, PA 15201, USA
Tel. (b)(4); (b)(6) [redacted]



Experimental Vehicle (XV) Model Overview

17 May, 2012

(b)(4); (b)(6) [redacted]

Carnegie Mellon University

National Robotics Engineering Center

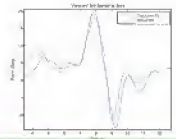
Ten 40th St.,

Pittsburgh, PA 15201

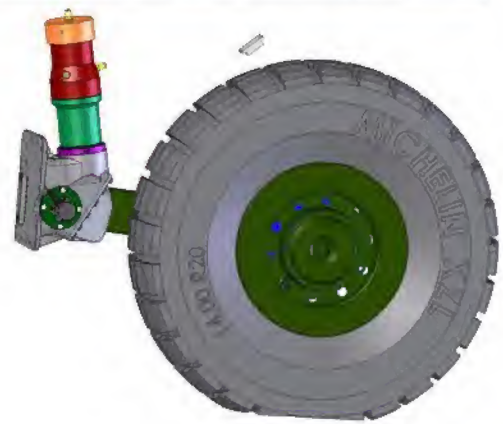
POC: (b)(4); (b)(6) [redacted]

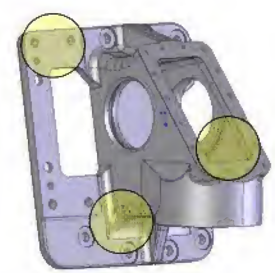
(b)(4); (b)(6) [redacted]

NREC Overview

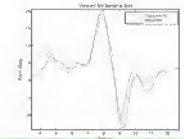


- **NREC Overview**
- **Experimental Vehicle (XV) Overview**
- **Design Methodology @ NREC**
- **Type & Identifier of Parts / Assembles** *(Time Permitting)*
- **Example Case** *(Live Cad Model)*





NREC Overview



Carnegie Mellon University

- 6000 undergrad; 5400 grad
- $865M operating revenue
- $318M sponsored projects

School of Computer Science

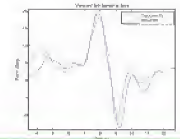
Robotics Institute

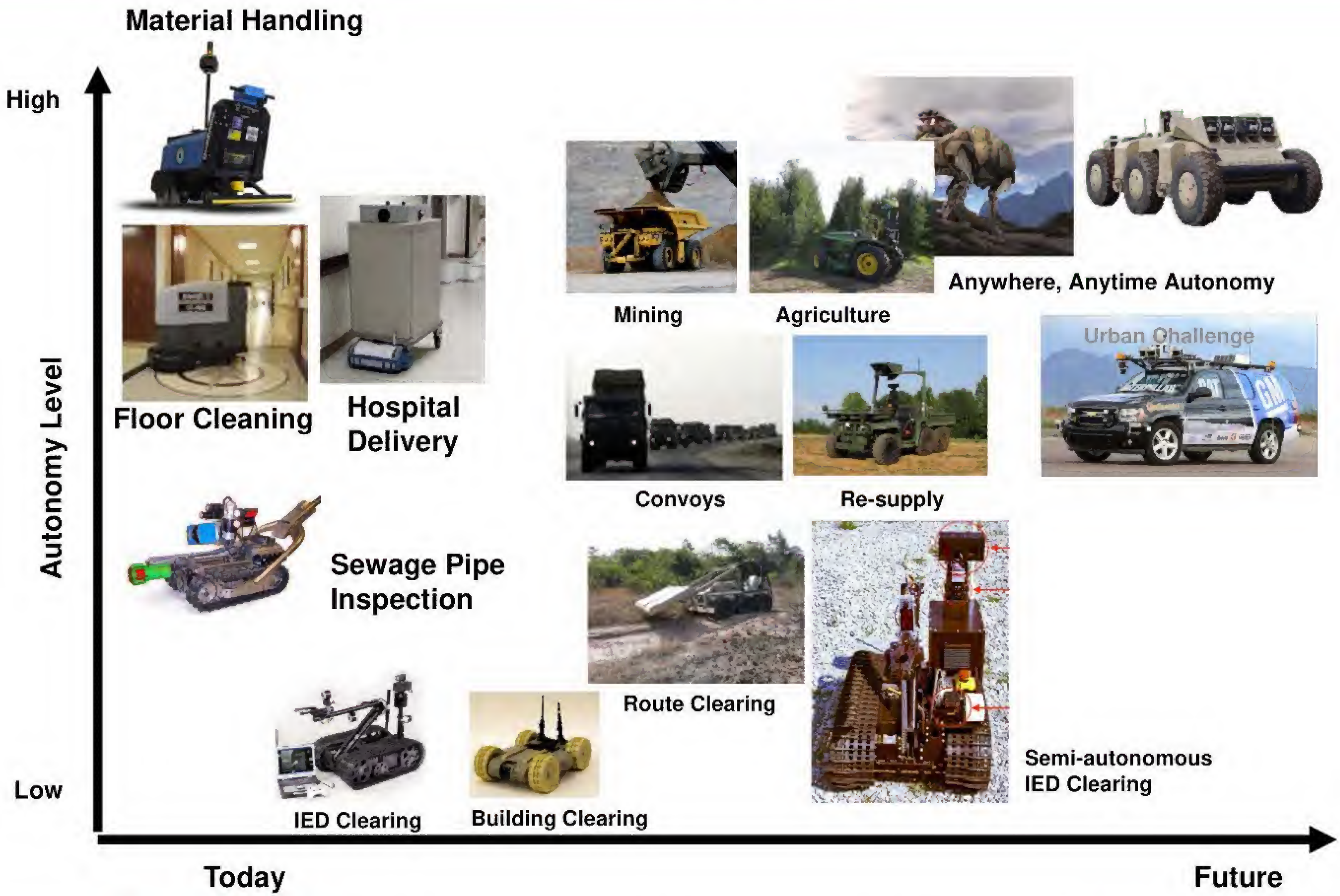
- ~ 450 faculty, staff, grad students
- MS and Ph.D in robotics
- $56M sponsored projects

National Robotics Engineering Center

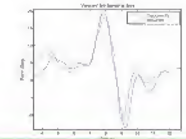
- 120 faculty, staff, grad students
- ~70% Staff
- ~$29M sponsored projects

NREC Overview





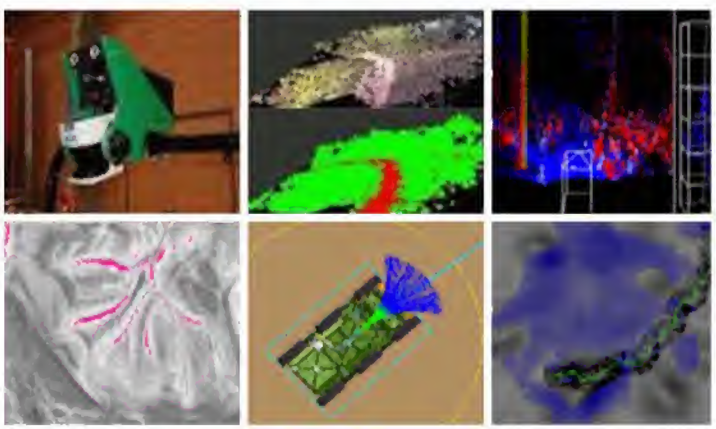
NREC Overview



Defense, Mining, Agriculture, General Industry

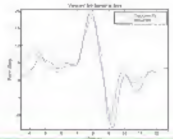
Integrated Platform Development & Evaluation

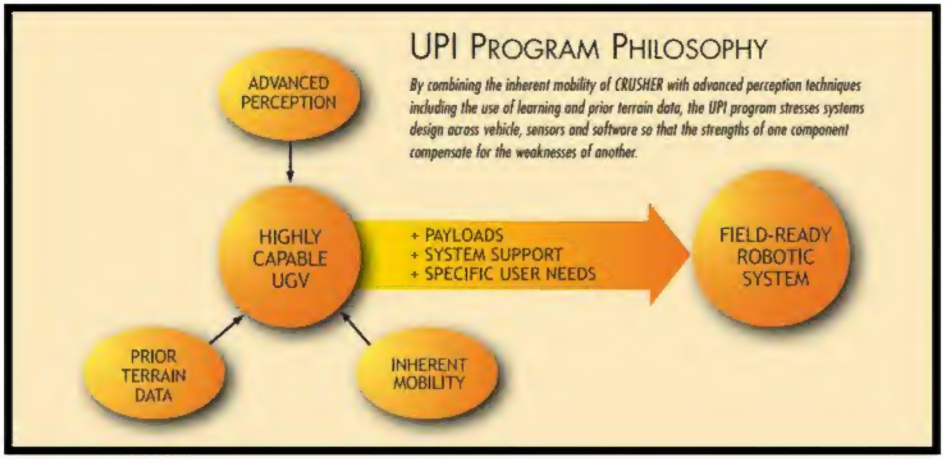
Autonomy & Perception



Smart Teleoperation & Vehicle Safety Systems

Experimental Vehicle Overview



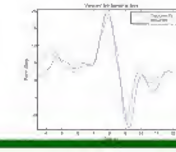


UGCV ("*CRUSHER*")

PerceptOR

UGCV PERCEPTOR INTEGRATION (UPI)

Experimental Vehicle Overview



UPI: Highly Mobile Autonomous Robotic Vehicle with Perception and Intelligence

Unloaded vehicle weight	13,200 lbs
Maximum payload/armor	8,000 lbs (maintaining capability)
Length	201 in
Width	102 in
Height (w/16 in ground clearance)	60 in
Ground clearance	0-30 in (reconfigurable)
Tire diameter	49.5 in
Top speed	26 mph (<7secs)
Minimum turning radius	0 (skid steer)
Slope climbing	>40 deg (traction limited)
Side slope	>30 deg (traction limited)
Step climb	>4 ft
Gap/trench crossing	>80 in
Engine	Turbo diesel
Generator output	58 kW/78 hp
Onboard battery storage	18.7 kW-hr energy
Traction motors	210 kW/282HP continuous
Peak torque	40,000 ft-lb (6WD)
Payload volume (internal)	41.6 ft^3 main bay (inside hull)
	16.1 ft^3 front bay (inside hull)
Payload power	28V, 5kW
	300V, 10kW
Control modes	Wireless pendant control (RC)
	Teleoperation control
	Waypoint following
	Full autonomy

NATIONAL ROBOTICS ENGINEERING CENTER

CAD Representation: UPI

Native CAD Program: <u>SolidWorks</u>

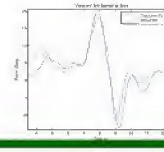
Number of Unique Parts: 1483

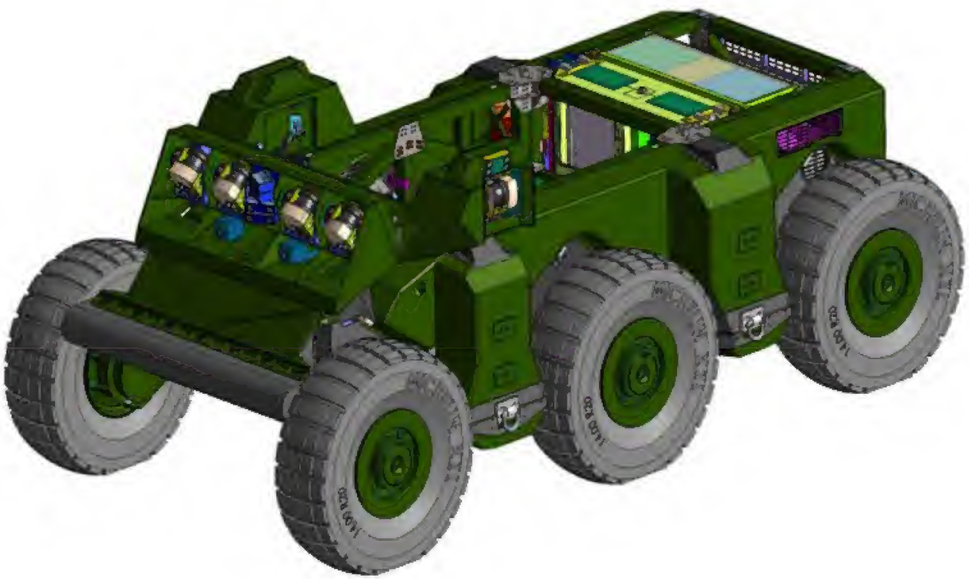
Total Number of Components: 5850

Number of Sub Assemblies: 352

Maximum Depth of Sub Assemblies: 5

Experimental Vehicle Overview





UPI TOP LEVEL ASSEMBLIES

SKIDPLATE

FRAME

WIRE HARNESS (ROUTING)

BATTERY COMPARTMENT

BRAKING SYSTEMS

FUEL SYSTEM

HIGH VOLTAGE SYSTEM

AIR CONDITIONING

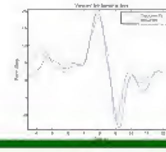
ELEVATOR SYSTEM
(LOW VOLTAGE COMPUTING)

EXTERIOR COVER PLATING

PERCEPTION SYSTEMS

SUSPENSION & DRIVE SYSTEMS

Experimental Vehicle Overview



ITEM NO.	DESCRIPTION	QTY.
[illegible]	[illegible]	[illegible]

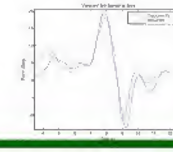
ITEM NO.	DESCRIPTION	QTY.	Process
1	**UPI_Suspension**	**3**	**Assembly**
1.1	HYDROSTRUT BEARING ASM	1	Assembly
1.2	HYDROSTRUT BEARING ASM, 2	1	Assembly
1.3	SUSPENSION STRUT MOUNT	1	Assembly
1.4	135ID X 5 ORING, STOCK	1	Stock
1.5	SEAL, QBAR04426	1	Stock
1.6	M16 X 2 X 40 FLATHEAD SCREW, STOCK	2	Stock
1.7	BACKING PLATE, BEARING BLOCK 2	1	WaterJet
1.8	M10 X 2 WASHER, STOCK	8	Stock
1.9	M10 X 1.5 X 30 HEX HEAD SCREW, STOCK	8	Stock
1.1	BEARING CAP, MACHINED	1	Machined
1.11	HYDROSTRUT OUTER CASE	1	Casting, Machined
1.12	SPANNER NUT, KML 28, STOCK	1	Stock
1.13	HYDARULIC VALVE, EMA 2-2_8EDA3C, STOCK	2	Stock
1.14	HYDRAULIC PLUG, VSTI3-8ED	4	Stock
1.15	ACCESS COVER, HYDROSTRUT, MACHINED	1	Machined
1.16	M8 X 1.25 X 25 HEX HEAD SCREW, STOCK	16	Stock
1.17	M8 X 1.6 WASHER, STOCK	16	Stock
1.18	LIMIT STOP BLOCK, HYDROSTRUT, STOCK	1	Machined
1.19	HYDROSTRUT MIDDLE CASE	1	Casting, Machined
1.2	HYDROSTUT CASE TOP CAP	1	Machined
1.21	RING SEAL, V7T41, STOCK	1	Stock
1.22	SWING ARM AND WHEEL COMPONENTS (ASSEMBLED)	1	Assembly
1.23	1400_R20_XZL_TIRE, MICHELIN, STOCK	1	Stock
1.24	Celesco RT8510-0R50-1X1-1120-632114A Transducer 180	1	Stock
1.25	SUSPENSION POTENTIOMETER MOUNT	1	Waterjet

UPI Bill of Materials

- Excel Format Table
- Directly Exportable from SW
- Can contain multiple metadata fields
- Nested sub-assembly structure

ITEM NO.	DESCRIPTION	QTY.	Process
1.25	SUSPENSION POTENTIOMETER MOUNT	1	Waterjet
1.25.1	WASHER, #8 FLAT NARROW (3/8 OD)	6	Stock
1.25.2	SCREW, #8-32 X 3/8 LG SHCS	6	Stock
1.25.3	HYDROSTRUT BEARING BLOCK 2 OUTER CASE	1	Machined
1.25.4	OUTBOARD JOURNAL, 30_03_05	1	Stock
1.25.5	BEARING SEAL, TIM POT	1	Stock
1.25.6	POTENTIOMETER, ROTARY SENSOR	1	Stock
1.25.7	OIL LIP SEAL, 1/2" SHAFT, 1 1/4 BORE, 1/4 THK	1	Syock
1.25.8	SHAFT, LONG POT, UPI	1	Stock

Design Process



PLANNING PHASE

Meet Customer → Determine Project Scope → Refine → Build Feature List → Concept → Analyze → Final Concept → Design Task List

Highly Mobile Robotic Platform
- Integrate sensors
- Integrate Intelligence
- **Performance in unstructured Environments**

Mission Requirements
- Operational run time
- Payload
- Speed

Environmental Requirements
- Sealing, Material Selection

Project Timeframe
- Time to execution
- Cost Limitations
- Material Limitations

Mobility Features
Modular Assembly
Handle Slopes
- 40 Deg Horizontal
- 30 Deg Side

Top Speed

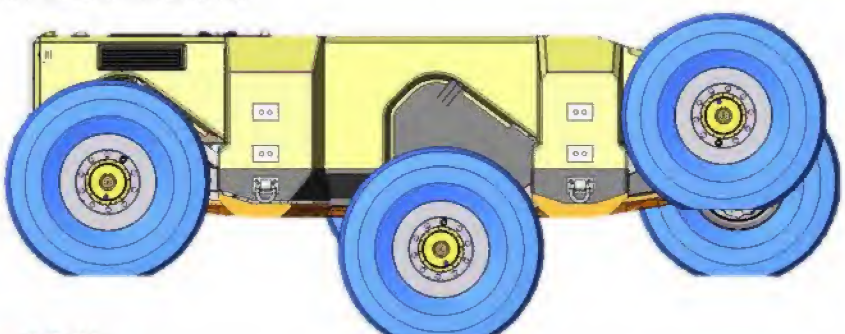
Tracks
Full Track
Half Track

Wheels
# of Wheels
Steering Type
Suspension Types

Ground Clearance
Payload Capacity
Speed Capability
Powertrain
- Hybrid Electric
- In-Wheel Electric Motors

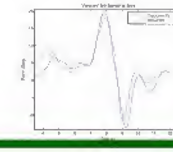
Suspension Type
- L-T-T Swing Arm Suspension

Battery Requirements
Computing Requirements
Overall Vehicle Size



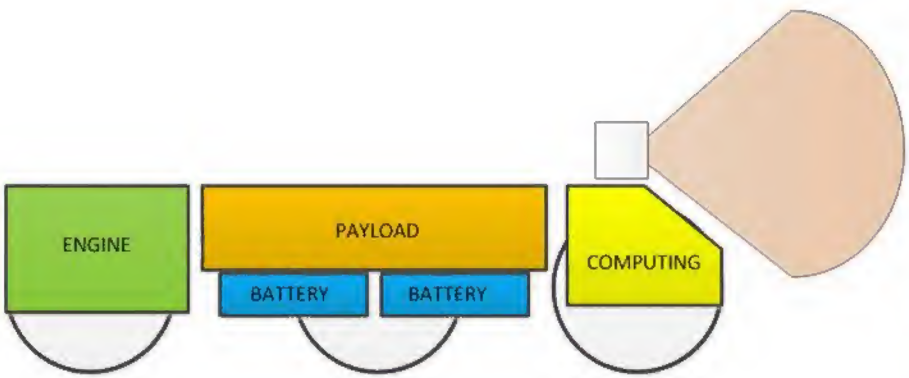
Goal:
- Quickly Converge to most practical solution to achieve goals.
- Have maximum time for design / production

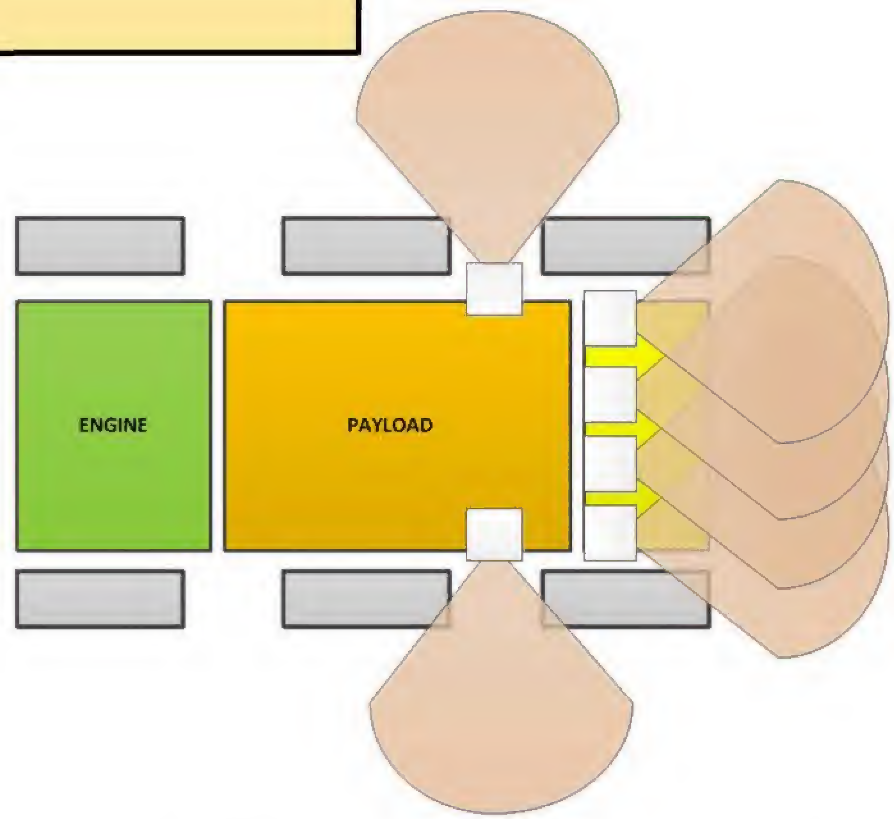
Design Process: Space Claim



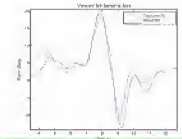
<u>Space Claim Driving Factors:</u>
- Known / Preselected Components
- Vehicle Dimension
- Ground Clearance
- Sensor Placement / FOV
- Payload Requirements
- Weight Distribution

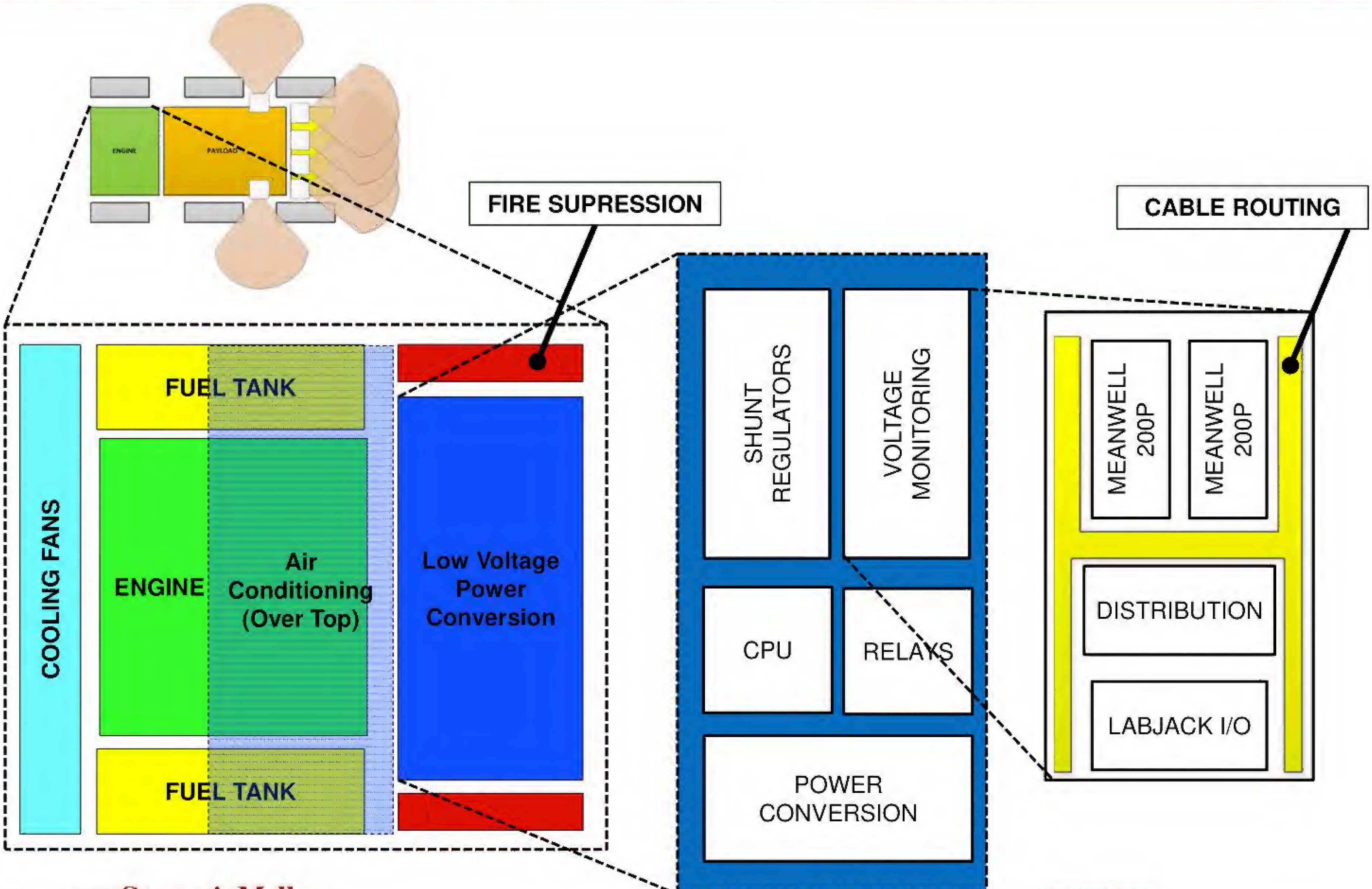
<u>Component Selection Preferences</u>
1. Lead Time
2. Performance
3. Dimensionality
4. Cost



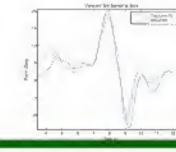


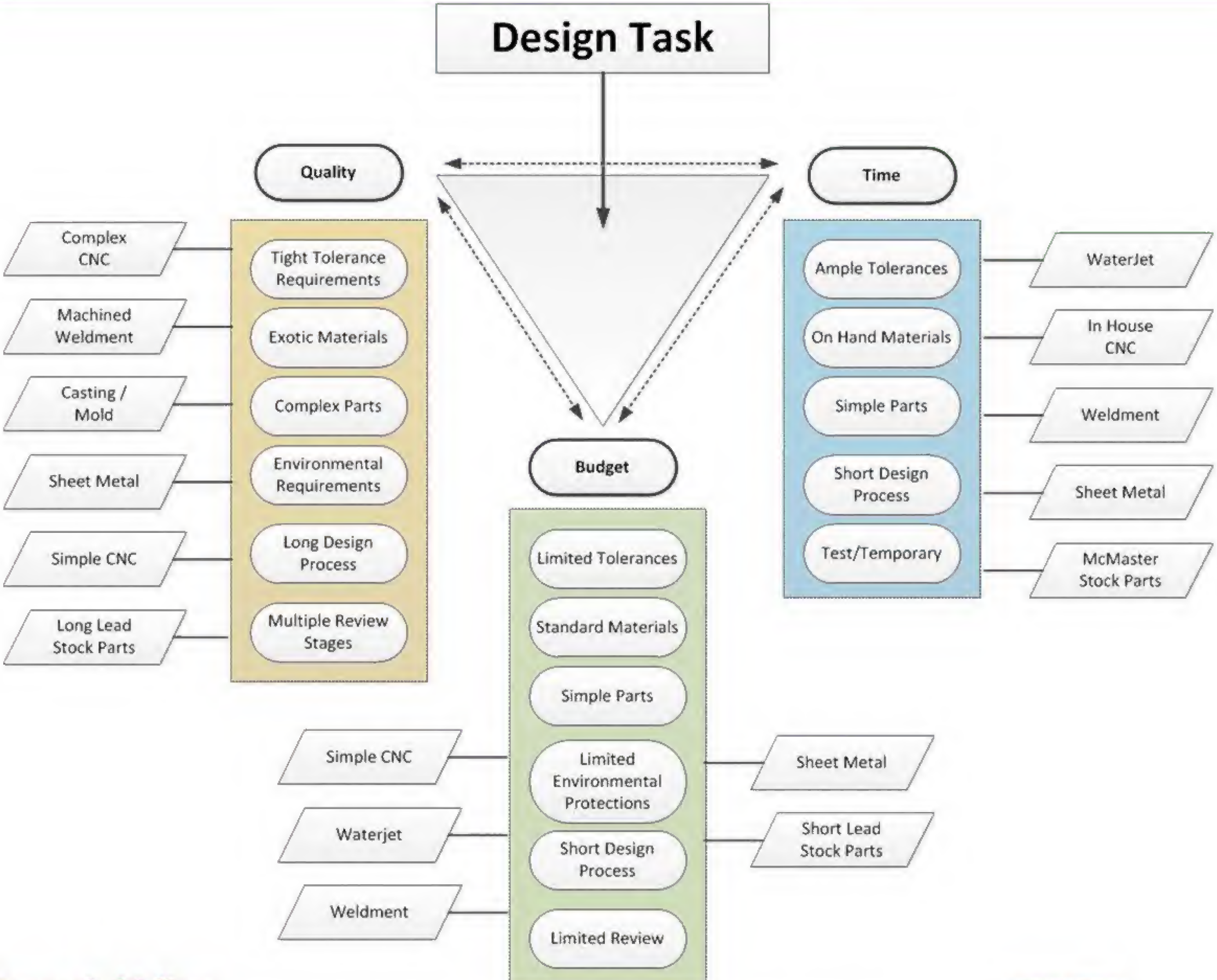
Design Process: Detailed Space Claim



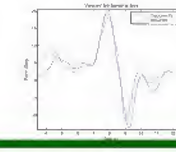


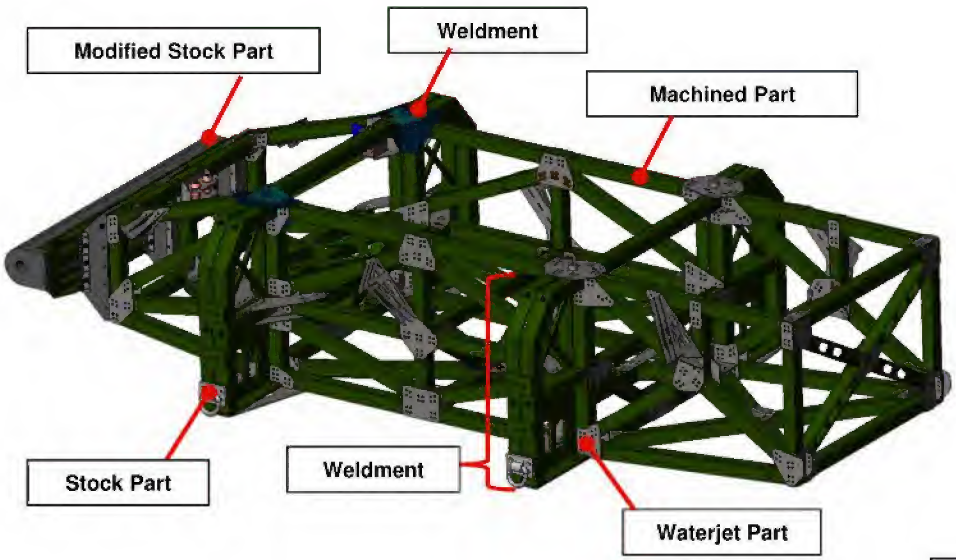
Design Decision Tree

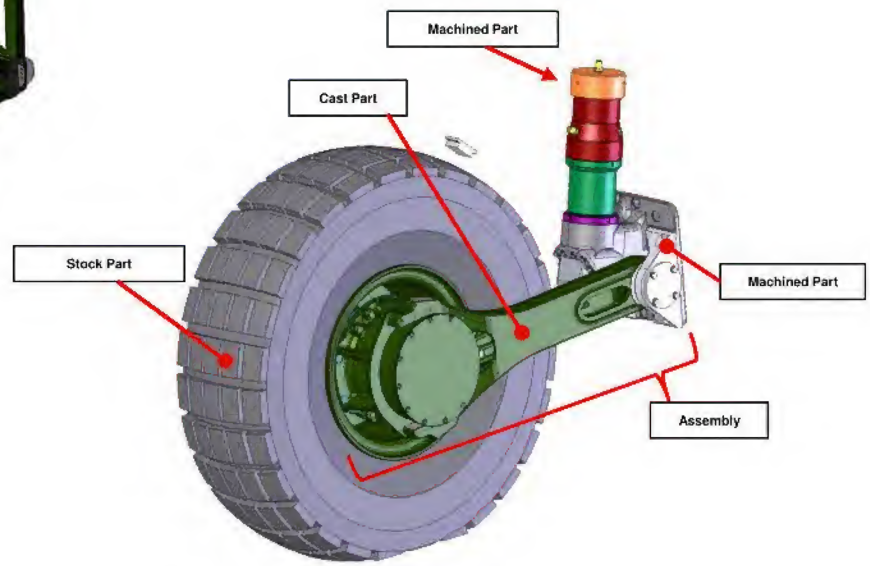




Part & Assembly Identifiers



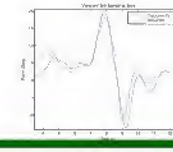




Points to Cover

- **How to identify different part types**
- **Why an NREC engineer chooses part / assembly types**
- **What are lessons learned / best practices**

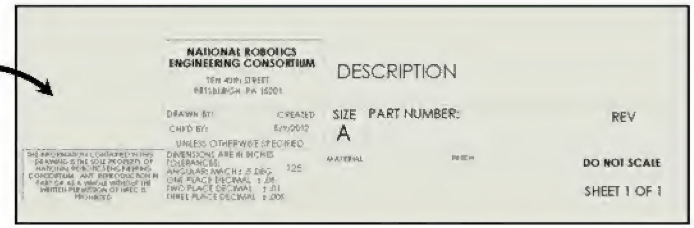
Part & Assembly Identifiers: Meta-Data



META-DATA (NEW PART – NREC Standard)

- **Used to populate fields on part drawing sheets**
- **Used to keep files organized in file management system**

	Property Name	Type	Value / Text Expression	Evaluated Value
1	FINISH	Text	SEE NOTES	SEE NOTES
2	MATERIAL	Text	SEE NOTES	SEE NOTES
3	REV	Text	0	0
4	AUTHOR	Text	AUTHOR	AUTHOR
5	DESCRIPTION	Text	ENTER DESCRIPTION	ENTER DESCRIPTION
6	AUTHORFULL	Text	AUTHORFULL	AUTHORFULL
7	PART NUMBER	Text	PART NUMBER	PART NUMBER
8	<Type a new property>			



Author / AUTHORFULL: Part drawing creator, sometimes "N/A" if not a custom part

(ex: G.J.G, G. GOLDMAN)

Description: Description of part type, machining type, and location in sub-assembly

(ex: Node_Plate,Corner_Node_Weldment,Frame_Assmebly)

Part Number: Designator of part. Can be either custom part number or stock company's stock number.

(ex: UPI-0236, MMC 2994T69)

Rev: Design revision of part. Usually only associated with custom parts (@ NREC)

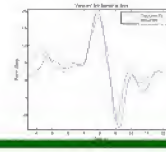
Material: Base material of part. Usually left as "Stock" for stock components.

(ex: Aluminum, 6061, Carbon Steel, Delrin)

Finish: Used if a special material finish is required.

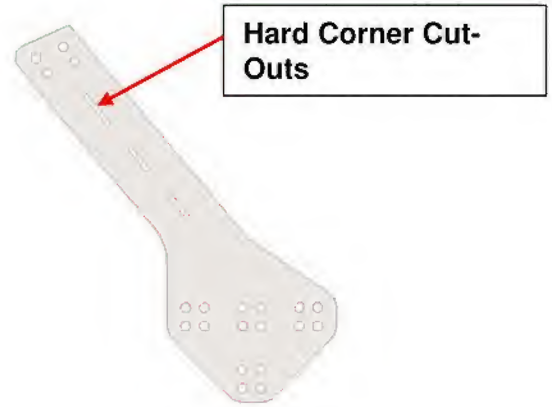
(ex: Black Anodized)

Part & Assembly Identifiers: WaterJet / LaserCut/ EDM



Part Geometry Identifiers – WaterJet / LaserCut/ WireEDM

- Slot and Tabs
- Planar components
- Hard edge or rounded cut-outs
- Holes & cut-outs are completely through part



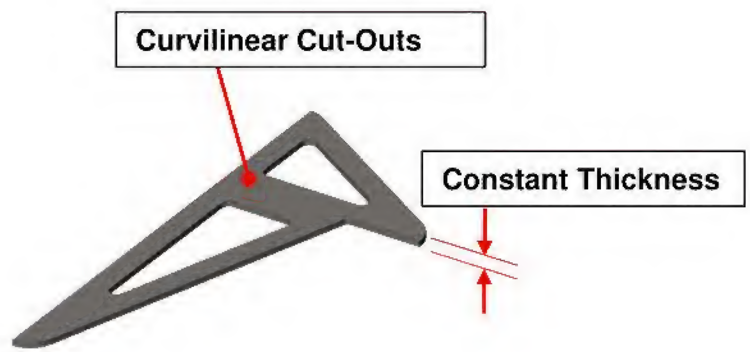
Design Benefits
- Low Cost
- Easy to Modify
- Very Quick
- Easily Scalable
- Large Selection of Materials
- Part Thickness
- Can have hard edges internal to part

Design Considerations

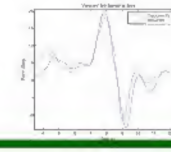
High tolerance stack up
- Extra clearance for ALL holes / slots / tabs
- Gap in between welded edges

Warping in thin parts

Conical cuts require touch up pass for bored holes
- Undersize holes that need to be exact tolerance
- Either post machine or hand bore



Part & Assembly Identifiers: CNC Mill / Molding / Casting



Part Geometry Identifiers – CNC Mill / Injection Mold / Casting

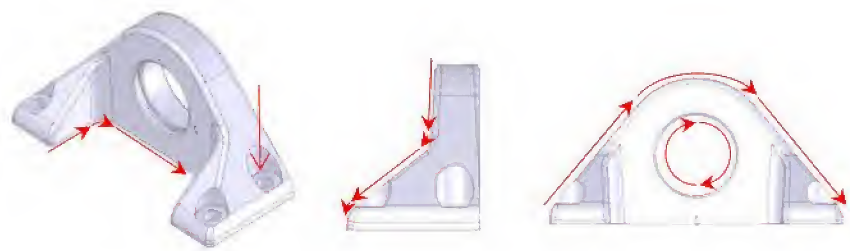
- Non-Planar features
- Curvilinear cut-outs
- Rare to have hard internal edges on cut-outs
- Features are formed from milling on multiple faces
- Usually orthogonal faces are used for milling surfaces
- Edges usually have fillets or chamfers
- Blind holes can be created using mill plunges
- Specialty mills can be used
  - → Undercutting
  - → Chamfering
  - → Radius
  - → Taps
- Standard mills used for many features
  - → Minimum radii on cuts
  - → Standard fillet radii
  - → Tapped holes have standardized sizes
- It is difficult to determine the difference between injection molding, casting, and CNC milled parts by geometry alone.
  - → Materials could give insight
  - → Other metadata should give designator for part type

Design Benefits

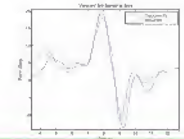
- Parts can be post machined to make changes
- Wide selection of metals and plastics
- Good tolerances (at a cost)
- Quick turnaround
  - In House Machine Shop
  - Relationships with External Shops
  - Pay our way out of time crunch (+30-50% cost)

Design Considerations

- Mindful of clearances between machined & stock parts
- Limit to standard sized CNC tools
- Specialty bits → more cost & time
- Design part to use standard tool dimensions
- Non-orthogonal planes → $$$
- Hard to do complex internal features



Part & Assembly Identifiers: Injection Mold / Casting



Part Geometry Identifiers –Injection Mold / Casting

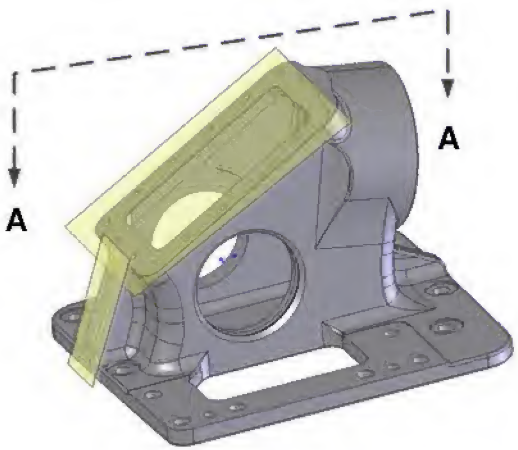
- Very similar to CNC Milled parts
- Has more interior features that would normally be reachable with standard mills
  - → Pockets
  - → Bosses
  - → Mounting points
- Has more non-orthogonal planes
  - → Would greatly increase set-up costs for CNC parts
  - → Each new plane is a new set-up that might required jigging parts on CNC

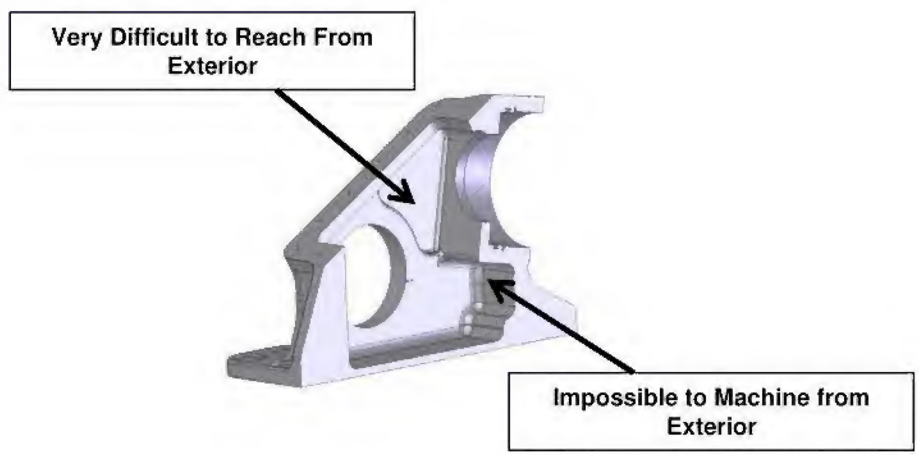
Design Benefits

- Material Control
- Very complex geometries (internal & external)
- Costs scale well for large quantities
- Non planar features
- Easier to optimize for loads

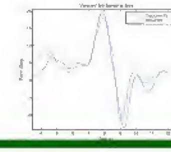
Design Considerations

- Longer engineering effort to design part and process
- Will most likely require post machining
- Long lead time
- Not efficient in small quantity





Part & Assembly Identifiers: Sheet Metal



Part Geometry Identifiers – Sheet Metal

- Could be both planar and non-planar versions of the same part
  - → Planar part is cut on laser cutter or waterjet
  - → Forming tools then shape it into a non-planar part
- Most edges have some curvature to them
- Consistent thickness on parts
  - → Some stamping and cold drawn parts will reduce thickness when new geometry is created
- Stamped and formed features usually use standard tools.
- Sheet metal parts could initially have un-connected edges that are connected post machining / forming
  - → Welding
  - → Rivets
  - → Fasteners

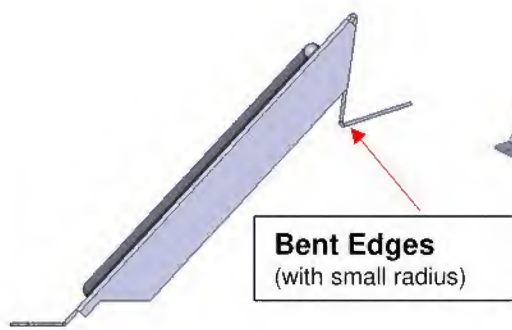
Design Benefits

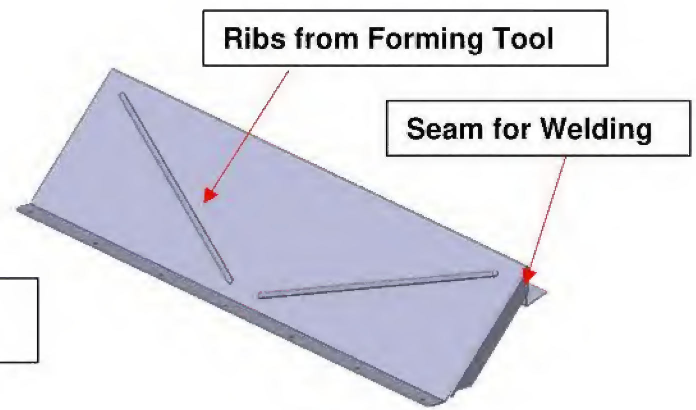
- Quick Lead
- Low Cost
- Scalable Geometry
- Non planar features
- Easily Integrate Hardware (PEMnuts)
- Can integrate into weldments

Design Considerations

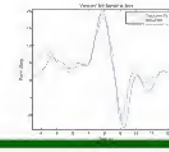
- Load Capacity
- Limited to geometries that produce flat pattern
- Limited Material Selection
- Limited part thickness
- Heat management during welding
- Allow for loose fit at mount points

Flat Pattern



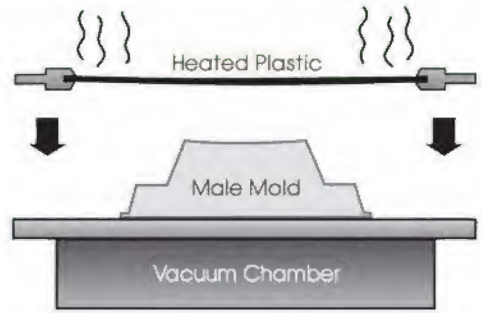


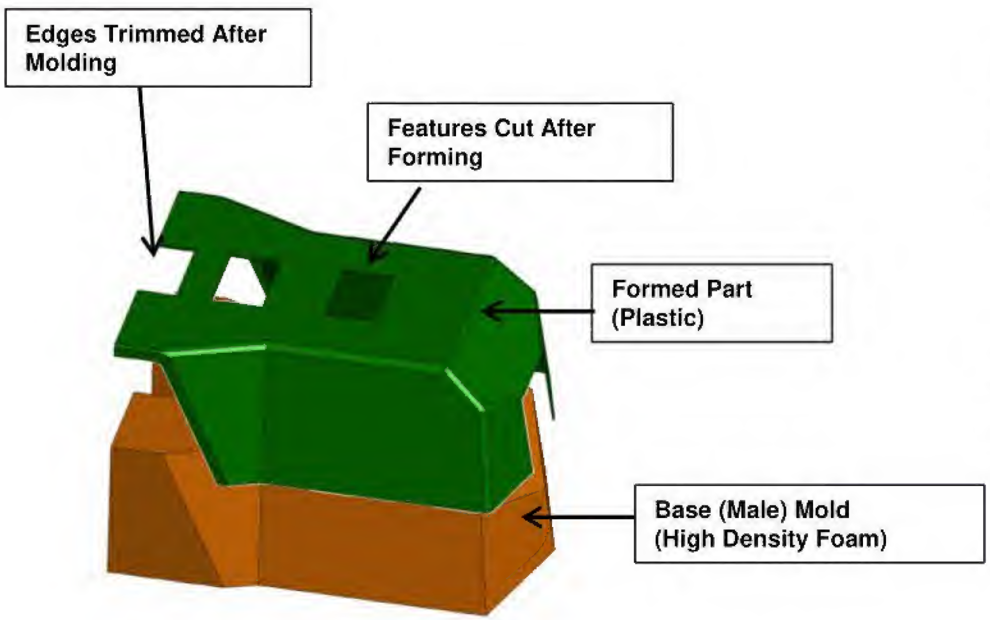
Part & Assembly Identifiers: Vacuum Mold



Part Identifiers – Vacuum Mold

- Usually plastic material types
- Consistent part thickness
- Usually has a main cavity volume where part was molded
- Edges do no have seams or gaps
- Does not have a “flat” version (compared to sheet metal)
- Possible that there is a second part configuration that shows the mold shape.





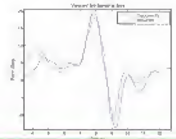
Design Benefits

- Possible to Rapid Prototype (if system is in house)
- Base Mold can be made from cheap materials
- Complex Geometries
- Large Size

Design Considerations

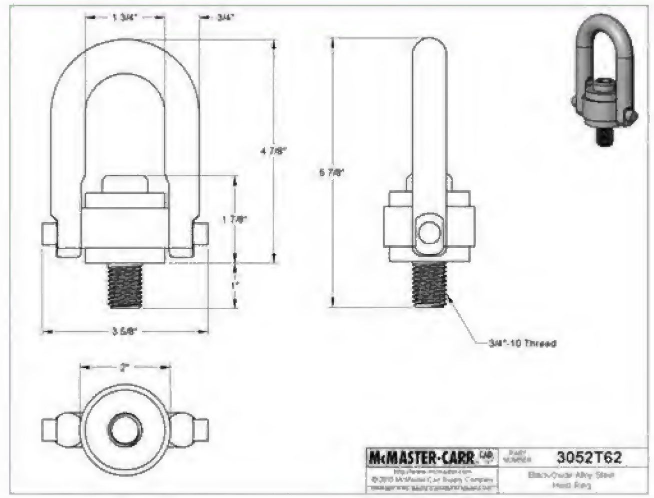
- Non-structural parts
- Additional hardware (inserts) needed for fastening
- Post forming trimming / machining might be required

Part & Assembly Identifiers: Stock Parts

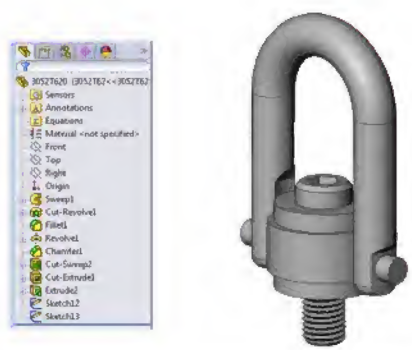


Part Identifiers – Stock Parts

- MetaData has best clues
  - → Part Number is not associated with project name (i.e. UPI-***** is project file)
  - → "Stock" in Material or description
  - → Standard sizes might be in description (i.e. ¼-20 bolt)
- Feature List might be very sparse
  - → Imported parts will not have feature list at all, only a imported solid body
- Could be single part or an assembly of parts
- Sometimes parts can be computationally heavy or unusable
  - → Mechanical engineer would modify or remake the part so it is simpler
  - → Redraw single parts into movable assemblies



Export From Supplier

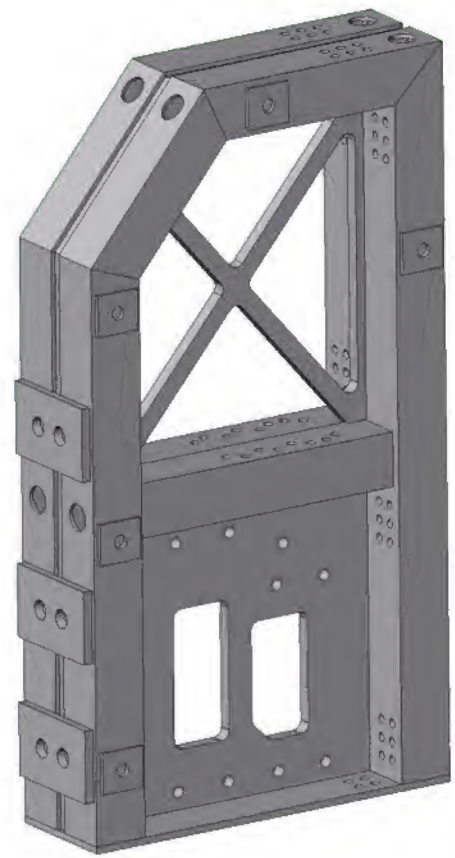


Redrawn as Assembly

	Property Name	Type	Value / Text Expression
1	Desc1	Text	Black-Oxide Alloy Steel
2	Desc2	Text	Hoist Ring
3	copywrite	Text	© 2010 McMaster-Carr Supply Company
4	<Type a new property>		

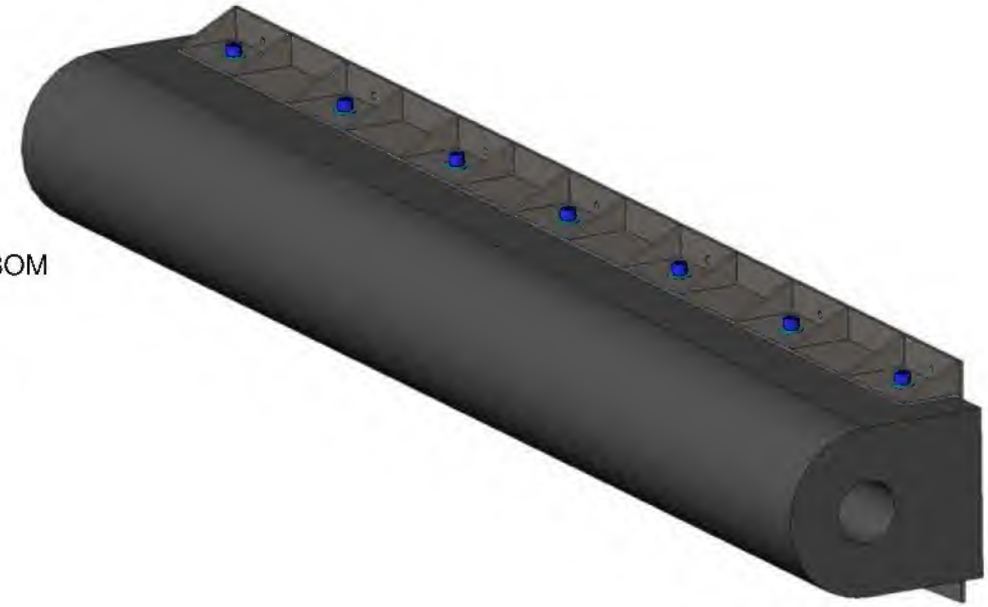
Assembly Identifiers – Weldments

- Possible to create complex geometries using multiple planar parts
  - → Used on the fame's tube structure multiple times
- Parts mated at hard edges
  - → Sometimes a gap is in assembly file to account for weld bead
  - → Sometimes there are alignment pins or jigs
- Most common parts are waterjet components
  - → Waterjet components are located via slot and tabs
- Common to see weld nuts or threaded inserts
  - → Weld nuts used with steel
  - → Threaded inserts used with aluminum and softer metals to reinforce threaded holes
- Can contain machined parts
  - → Easy to pick out compared to waterjet plates
  - → Example would be a machined shaft to maintain concentricity between multiple waterjet plates
- Could also be post-machined after welding
  - → This process could be repeated multiple times
- Possible to have high tolerance stack up
  - → Gap between slot and tabs is 0.2 mm (0.008")
  - → Metals flexes due to heat during welding
  - → Holes for assembly onto other parts have conservative tolerances to account for slop



Assembly Identifiers – Fastened Assemblies

- Parts / Assemblies attached to each other through standard fastening methods
  - → Stock Fasteners Used
  - → Standard Sizes
- Possible to have seals or spacers in between parts
  - → Rubber gaskets
    - – Or any common deformable material
  - → Washers
- Has at least one level deep of parts or sub-assemblies in BOM
- Tolerances between parts are minimal
  - → Assembled faces are considered to be touching at zero gap
  - → Fastening holes should be concentric
- Rare to have post machining on a fastened assembly

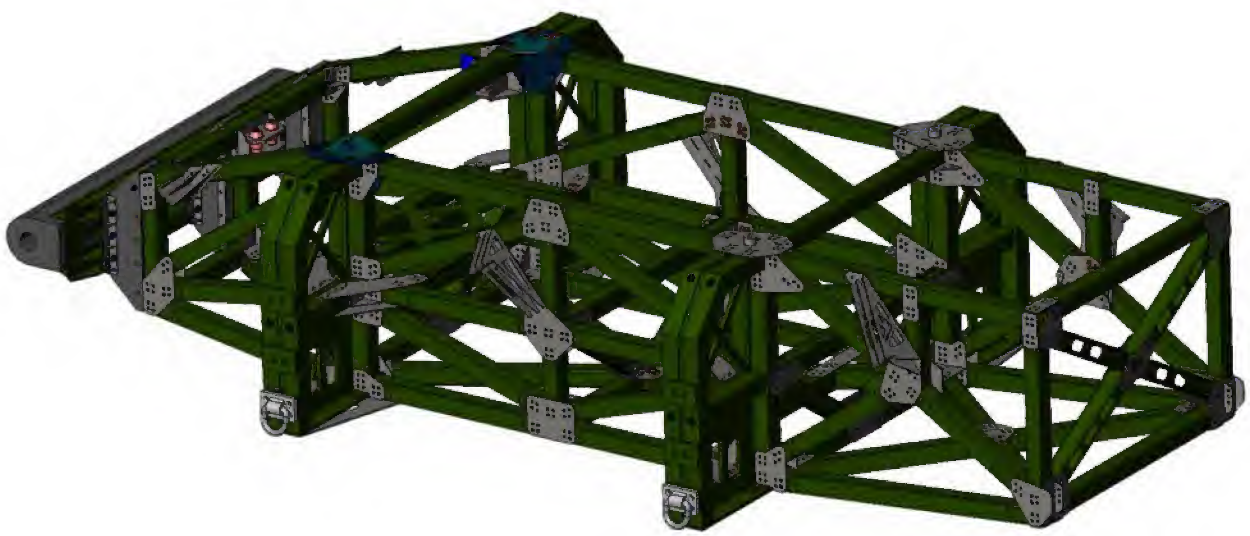


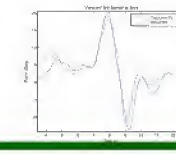
UPI FRAME

- Show example parts / assemblies
- Explain why part / assembly types were chosen
- Go from assembly level down to part level

-Model Will be Available Shortly (~1 Week)

-Native SW Files and Parasolids





Contact Information

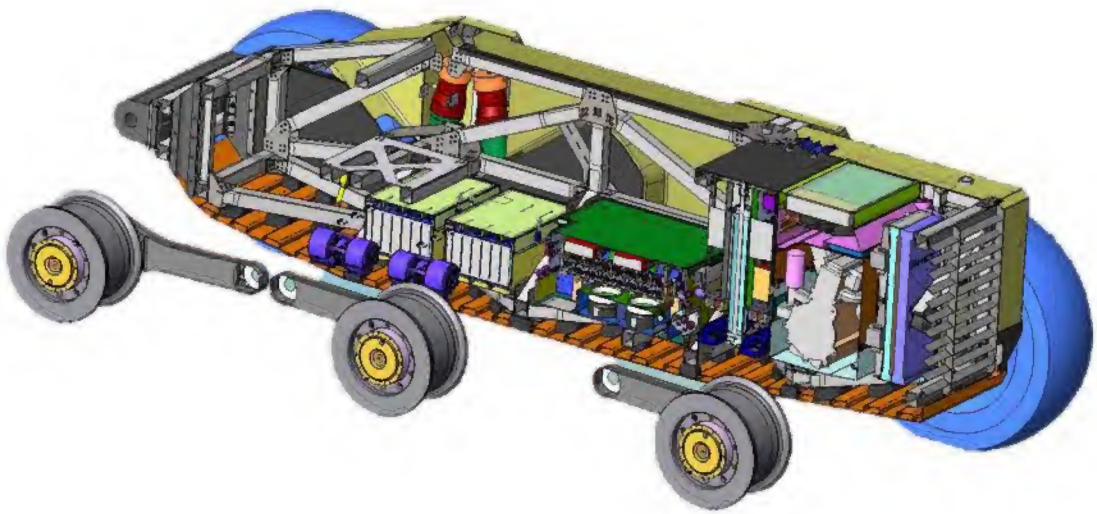
(b)(4); (b)(6) [redacted]

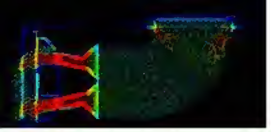
National Robotics Engineering Center

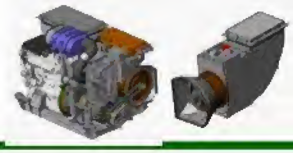
(b)(4); (b)(6) [redacted]

POC: (b)(4); (b)(6) [redacted]

(b)(4); (b)(6) [redacted]







Experimental Vehicle (XV)
Thermal Management

30 Nov 2011

(b)(4); (b)(6) [redacted]

Carnegie Mellon University

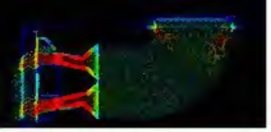
National Robotics Engineering Center

Ten 40th St.,

Pittsburgh, PA 15201

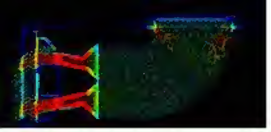
POC: (b)(4); (b)(6) [redacted]

(b)(4); (b)(6) [redacted]



Forward

- Vehicle/Thermal systems Overview
- Model Overview
- Simulink model
- Inputs
- Kuli model
- Outputs
- Model details



Forward

- **Reference information – useful during setup and operation of model**

Abbreviation	Meaning
AC	Air conditioner
BPHX	Bypass (counter flow) heat exchanger
CAC	Charge Air Cooler
DCDC	DC-DC Converter
EGW	Ethylene Glycol Water
hPa	Hectopascal (millibar)
HV	High Voltage
HX	Heat Exchanger
kph	kilometers per hour
kW	kilowatt
LF	Left front
LM	Left middle
LPM	Liters per minute
LR	Left rear
LV	Low Voltage
MV	Medium Voltage
PGW	Propylene Glycol Water
RF	Right front
RM	Right middle
RPM	Revolutions per minute
RR	Right rear
SA	Sub-ambient
SCFM	Standard cubic feet per minute
V	Volt
XV	Experimental Vehicle

Simulink Model:
C:\ECS\KULI_80102\data\forMatlabWork\XV_Full.mdl

Init Fcn callback:
C:\ECS\KULI_80102\data\forMatlabWork\HeatLoads.m

Init Fcn callback inputs:
C:\ECS\KULI_80102\data\forMatlabWork\STEM_Data\HighSpeed80kph\PAResults.csv
C:\ECS\KULI_80102\data\forMatlabWork\STEM_Data\Dirt45kph\PAResults.csv
C:\ECS\KULI_80102\data\forMatlabWork\STEM_Data\MaxGrade5kph\PAResults.csv

Kuli Model:
C:\ECS\KULI_80102\data\CoolingSystems\XV_Full.scs

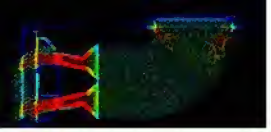
Kuli Application:
C:\Program Files (x86)\ECS\KULI_80102\Program\Kuli.exe

S-function:
C:\ECS\KULI_80102\data\forMatlabWork\KULI_server.m

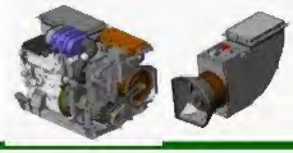
COM File Location:
C:\ECS\KULI_80102\data\forMatlabWork\COM_Definition_XV_Full.xls

Results:
C:\ECS\KULI_80102\data\Results\XV_Full.scsPost

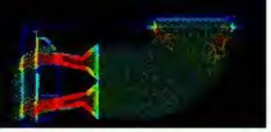
Matlab version:
R2009a, 32-bit



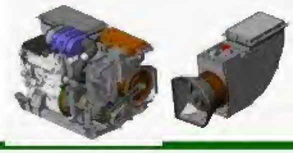
Overview - XV



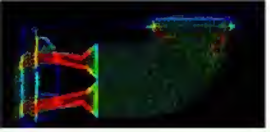
- Experimental Vehicle (XV) key requirements
  - → Mobility requirements – steady state stressing cases (80 kph, flat, pavement; 45 kph, flat, dirt; 5 kph, 60% grade, pavement)
  - → Objective: Mobility requirements at 45 C ambient, full solar with ballistic grills
  - → Threshold: Full capability at 25 C without ballistic grills
- Developed, adjusted and validated thermal models then built XV
- XV Testing
  - → Component Testing: early and often, found and fixed problems early
  - → Dynamometer (Vehicle) Testing: high power, ambient conditions up to 45 C, temperature controlled chassis dynamometer = most thermally demanding mobility requirements; reached temps just shy of 45 C)
  - → Vehicle Testing: outdoor environment, temperatures reached 43 C



XV Challenges

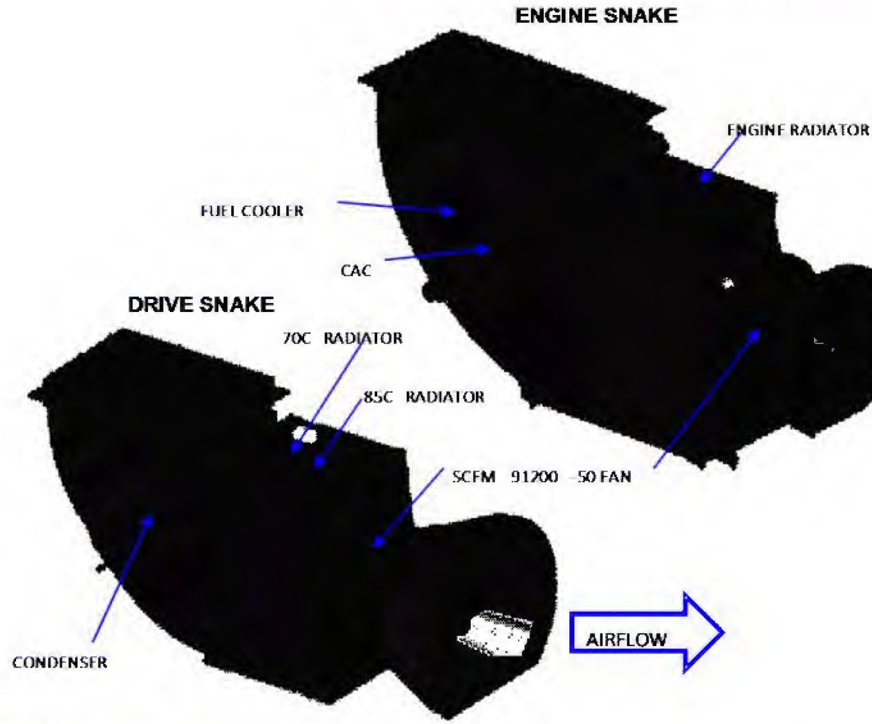


- **High performance (vehicle, mission equipment)**
- **Rejecting heat**
  - →**Limited volume for air flow**
  - →**Ballistic grills**
  - →**High ambient temperature**
  - →**Dust**
  - →**Coolant flow limits**
  - →**Wide ranging inlet temp & flow rate**
  - →**Sub ambient necessary**
  - →**Pump, compressor and fan power management (design perspective)**
- **Thermal modeling complex – thermal system matches model (each has four cooling loops)**
- **Thermal model uses Matlab/Simulink and Kuli**



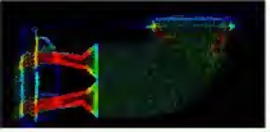
XV Thermal System Overview

- Two air paths
  - → Engine Snake (High temp): Engine & Charge Air Cooler (CAC)
  - → Drive Snake (Low temp): Electronics, generators, motors



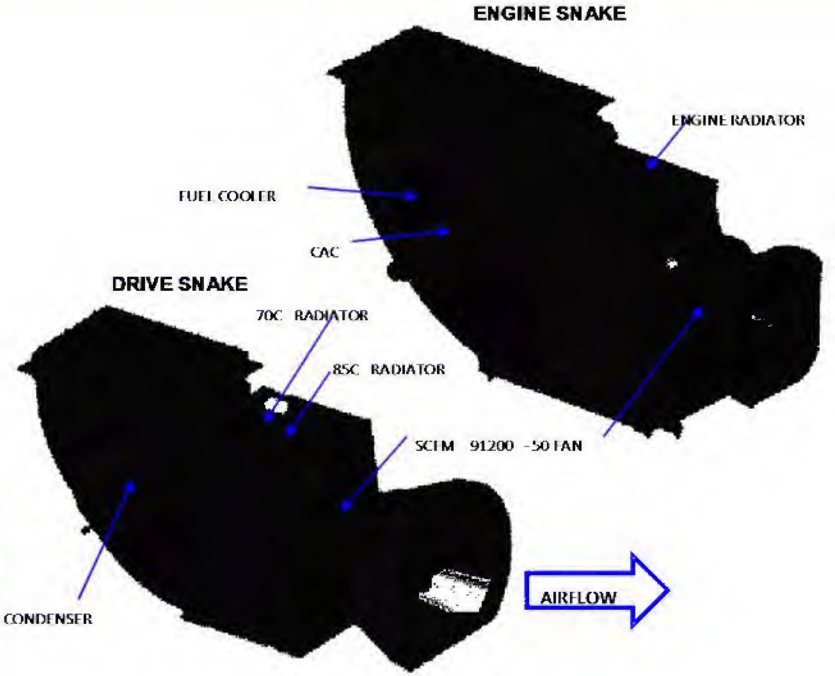
XV Engine and Drive Snake

AIRPATH 1 - Port Side (Drive Snake)		AIRPATH 2 - Starboard Side (Engine Snake)	
Heat Exchanger	**Design Heat Rejection and Coolant Spec**	**Heat Exchanger**	**Design Heat Rejection and Coolant Spec**
A/C System Condenser (Batteries and Misc Electronics)	10 kW - 40 LPM @ 10 C (Chilled Coolant)	*Single Pass Charge Air Cooler*	60 C (Air)
Single Pass Radiator (HV Electronics and Aux Motors/Generators)	12 kW - 225 LPM @ 70 C	*Quad Pass Radiator (Engine and Brake Shunt Resistor)*	120 kW - 180 LPM @ 95 C (Coolant)
Dual Pass Radiator (Wheel Motors and Main Generator)	35 kW - 85 LPM @ 85 C		
Fan Airflow Estimate	**Fan Power**	**Fan Airflow Estimate**	**Fan Power**
5100 SCFM @ 6100 RPM	10 kW Electrical @ 6100 RPM (Electric Motor Driven)	8600 SCFM @ 10,000 RPM	43 kW Mechanical @ 10,000 RPM (Electric Motor or Engine Drive; both via Belt)



XV Thermal System Overview

- **Four liquid loops**
  - → Engine (high temp)
  - → 85 C (motors & generators)
  - → 70 C (secondary generator, controlling electronics)
  - → Sub-ambient (mission equipment)



DESCRIPTION OF COOLED COMPONENTS			
DRIVE SNAKE		ENGINER SNAKE	
SUB-AMBIENT LOOP		FUEL COOLER	
10 kiwi MAX - 40 LPM WGW MAX at 10 C NOMINAL		60 c MAX FUEL TEMP	
COMPONENT	QUANTITY	COMPONENT	QUANTITY
LV Electronics Enclosure	1	Engine Fuel (DF2 or JP8)	1
HV Electronics Enclosure	1		
Controller w/ Cold Plate	2		
Turret	1		
Battery Enclosure	2		
70C LOOP		CHARGE AIR COOLER	
12 kW MAX - 225 LPM EGW MAX at 70 C MAX		60 C MAX AIR TEMP	
COMPONENT	QUANTITY	COMPONENT	QUANTITY
Wheel Motor Controller	6	Engine Charge Air	1
Generator Controller	1		
Brake Chopper Shunt Controller	2		
350 V - 750 V Convertor	2		
350 V Motor/Generator	1		
Generator Controller	1		
Drive Snake Fan Motor	1		
350 V to 12/28 V Convertor	3		
85 C LOOP		ENGINE LOOP	
35 kW MAX - 85 LPM EGW MAX at 85 C MAX		20 kW MAX (Engine Only) - 180 LPM EGW MAX at 95 C MA	
COMPONENT	QUANTITY	COMPONENT	QUANTITY
Wheel Motor	6	Engine	1
750 V Generator	1	Brake Shunt Resistor (40 kW Max Expected)	1

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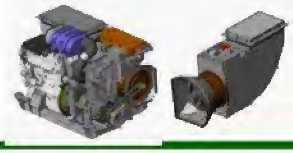
XV – Engine Loop



- **FUEL COOLER –**
  - → **Maintained fuel temps in working range, no reduction in power on hot day**
- **CHARGE AIR COOLER –**
  - → **Parallel air flow w/ fuel cooler**
  - → **Functioned as modeled**
- **ENGINE LOOP**
  - → **Maximum expected engine heat + 20% margin over test data used in model (fouling etc.)**
  - → **Expected engine bay to be hot on cloudless summer day in hot region - separate fan to vent engine bay a good approach**
  - → **Maximum measured engine coolant flow rate used at max steady state load (mobility driven)**
  - → **Prescribed shunt coolant inlet temperature maintained**
  - → **Engine coolant inlet temperature predicted matched actual for conditions similar to model (cloudless hot summer day)**
  - → **Engine never limited power (coolant = 105 C)**

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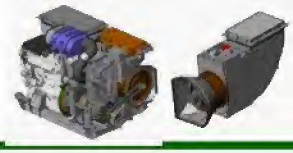
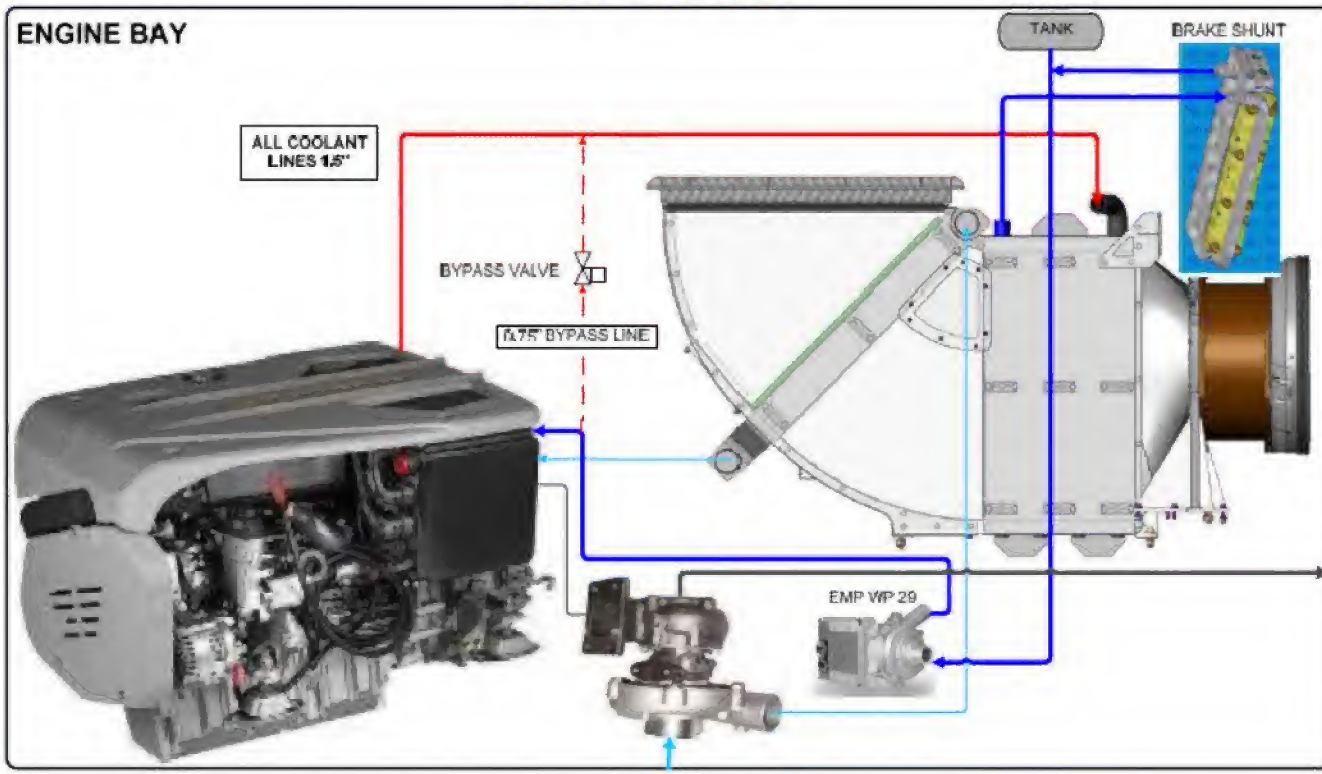
XV – Engine Loop



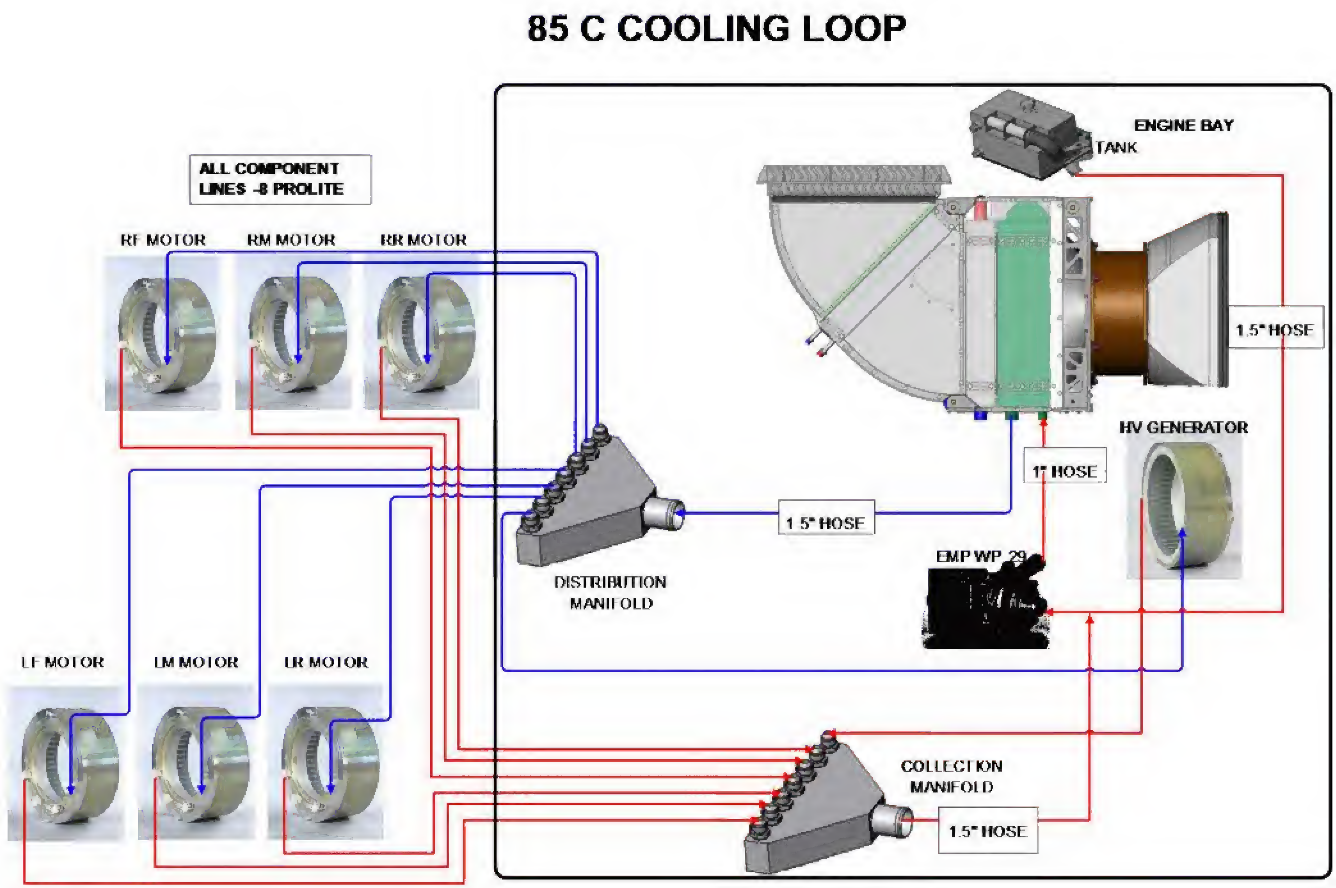
- **Shunt cooling when engine off**
  - → Bypass valve and electric pump
  - → Coolant flow lower than equipment spec
  - → Coolant temp lower than equipment spec
  - → Good performance

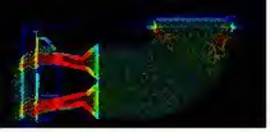
ENGINE COOLING LOOP



XV – 85C Loop

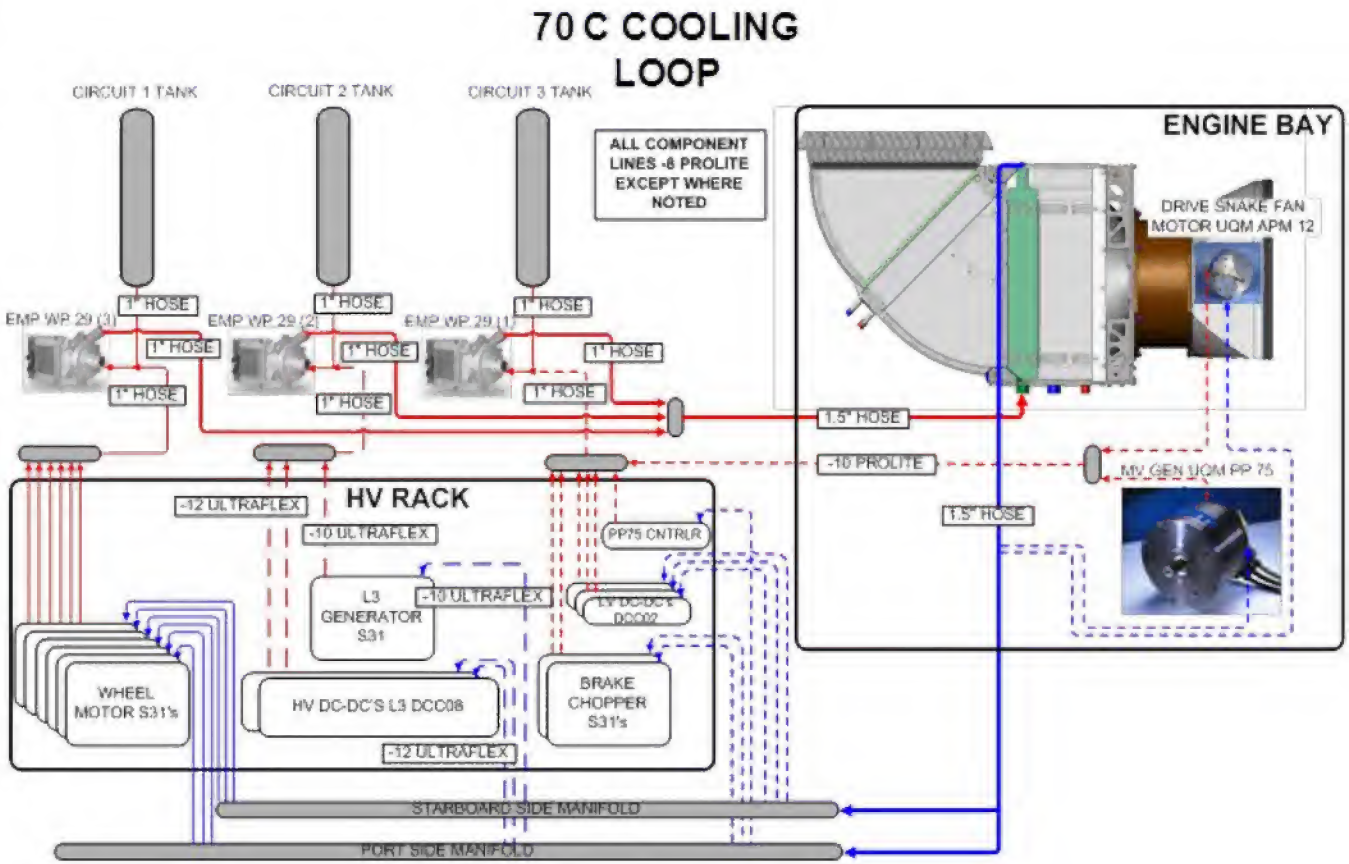
- Max load 80kph, 45C model & actual
- Flow rate – has margin, pumps not at full speed
- Loop as thermal margin, other equipment could be added
- Simplest loop

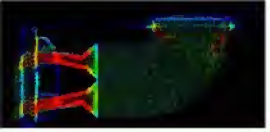




XV – 70C Loop

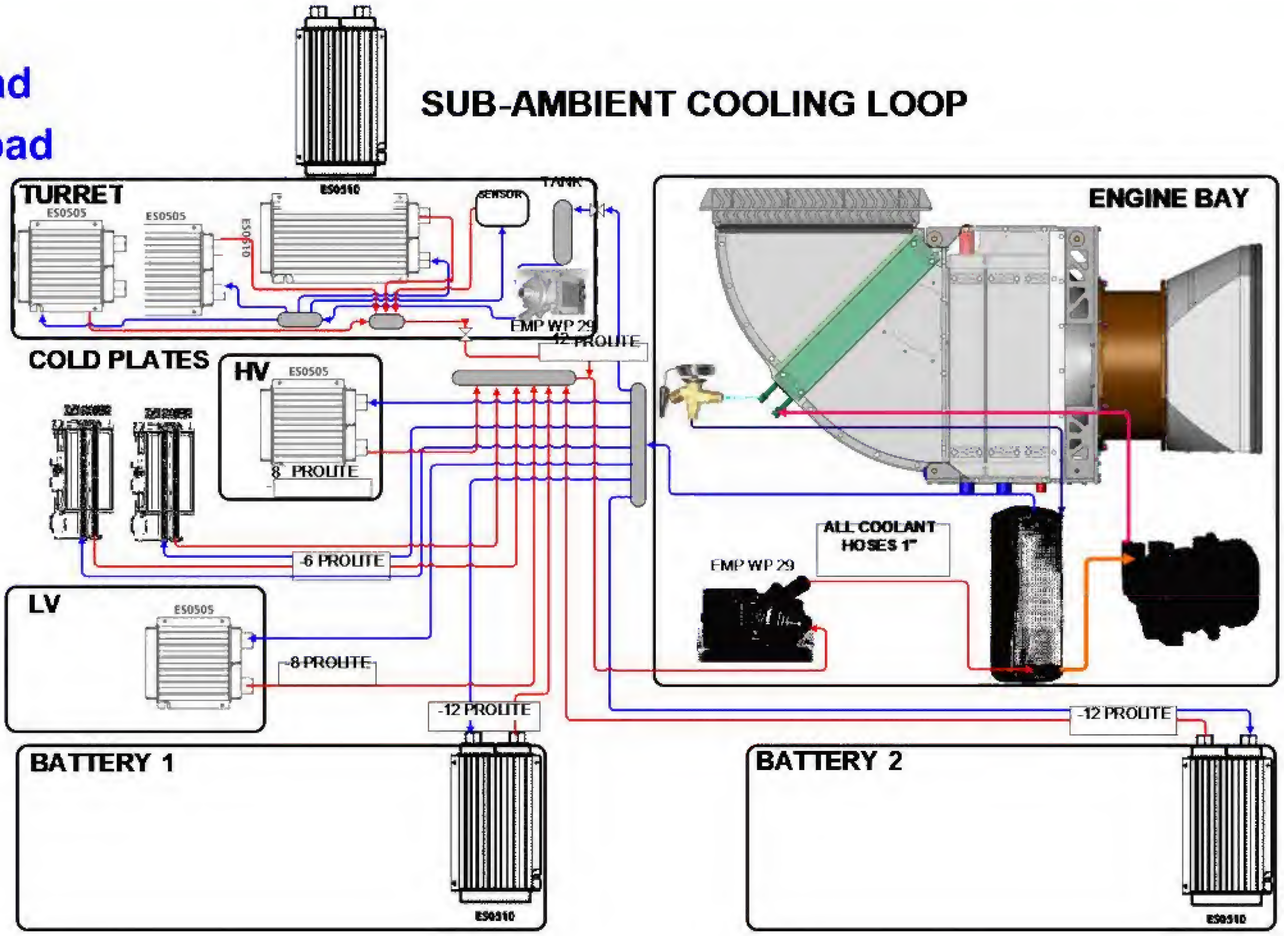
- Max load 80kph, 45C model & actual
- Flow rate – slightly less than needed after quick disconnects installed (losses)
- Loop at limit (model & actual)
- 70C loop limited performance
- Slightly higher coolant flow rate – XV would have run at 45C, full solar

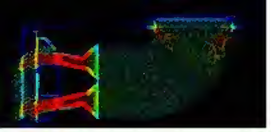




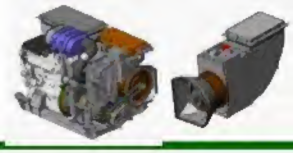
XV – Sub-Ambient Loop

- **Capacity**
  - → Max Eqpt & Vehicle Load
  - → 45C ambient w/ Solar load
- **Air over heat xchg**
  - → Turret = all mission equipment
  - → LV = LV PDU
  - → HV = HV PDU
  - → Battery Packs
- **Cold plates = Ctrls**
  - → Drive Snake Fan
  - → Compressor





Model Overview – Basic Operation



- **Model operations**
  - → Set stressing case in Heatloads.m
  - → Run Simulink
  - → Results can be viewed on Simulink Scopes, saved to Matlab workspace then plotted, or viewed in the Kuli post processing file
  - → Detail instructions can be found in the ReadMe_XV… document
- **Modeling Assumptions**
  - → All components thermally soaked at ambient temperature (45C)
  - → Vehicle starts and is driven at one speed, one engine setting (series hybrid)
  - → Components temperature increase then operate at steady state

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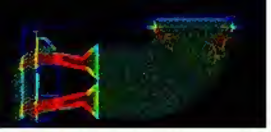
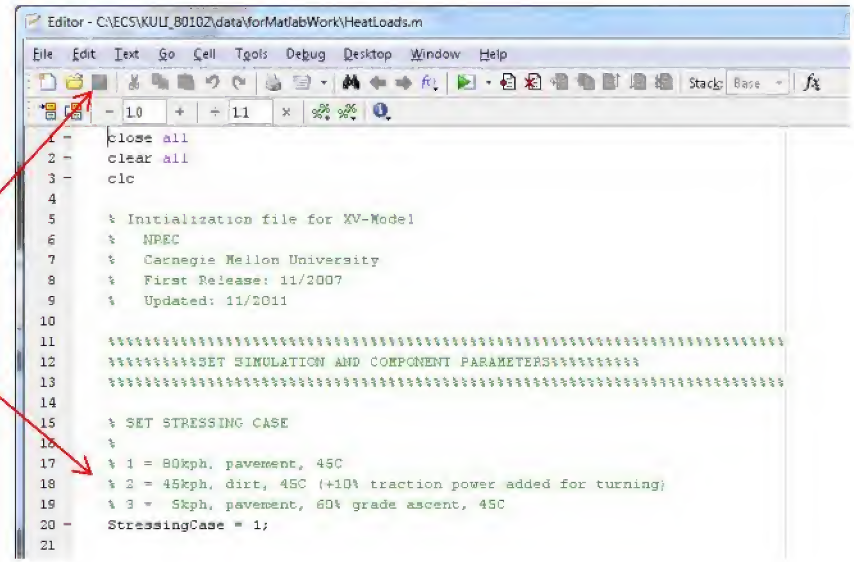
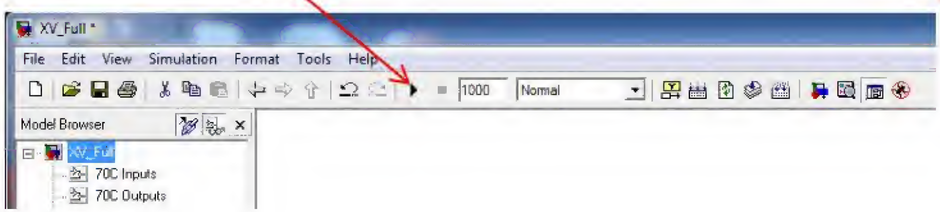


Model Overview – Basic Operation

- **Steady state thermal loads and power for three stressing cases (PAResults.csv)**
  - → **80 kph, flat, pavement (1)**
  - → **45 kph, flat, dirt (2)**
  - → **5 kph, 60% grade, pavement (3)**
- **Basic operations**
  - → **Set stressing case in Heatloads.m, save**
  - → **Push Start in XV_Full Simulink Model**





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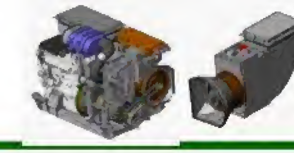
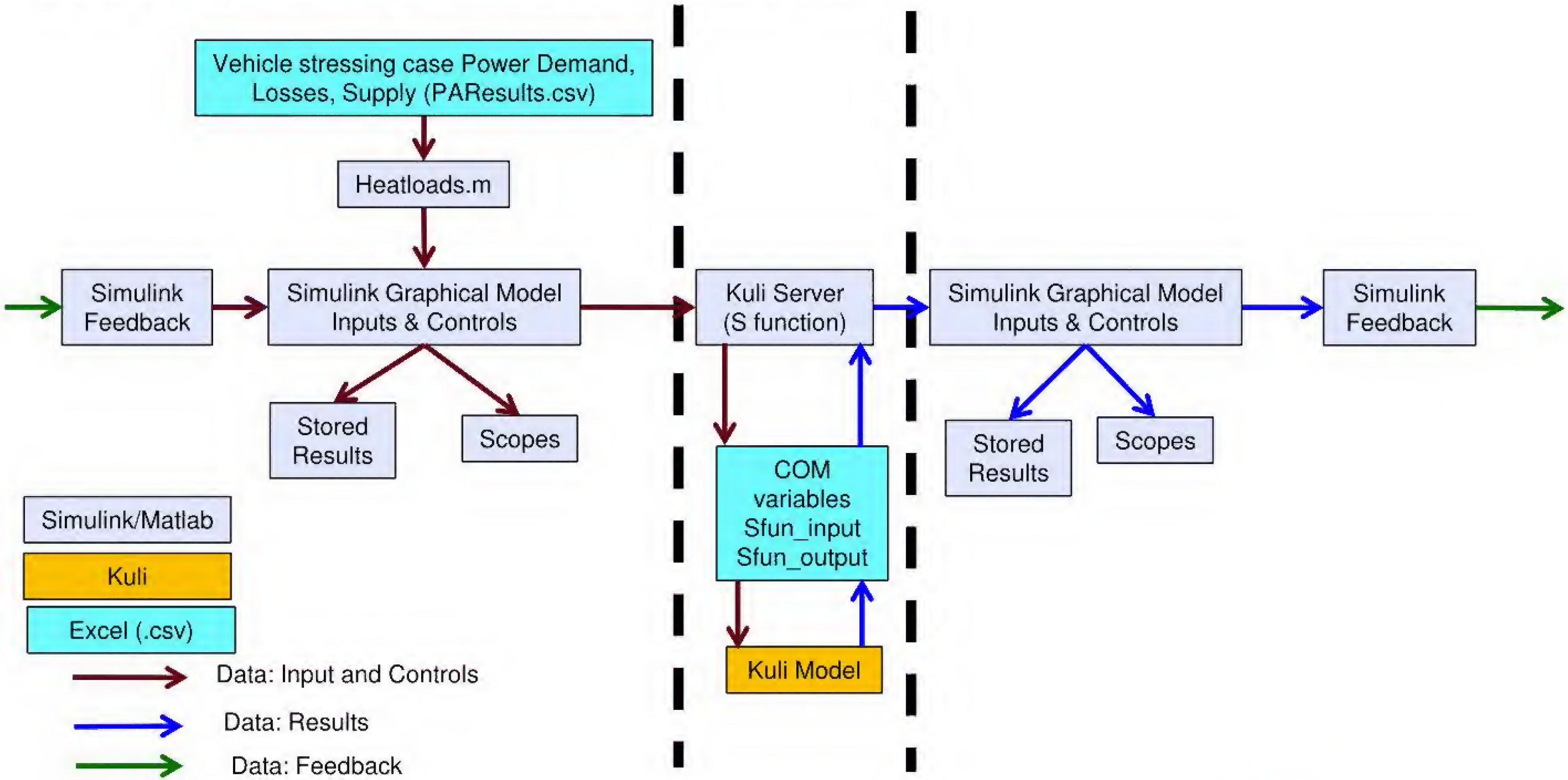
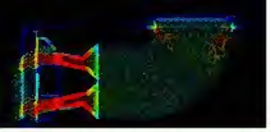
Model Overview – Basic Structure

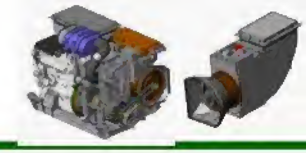


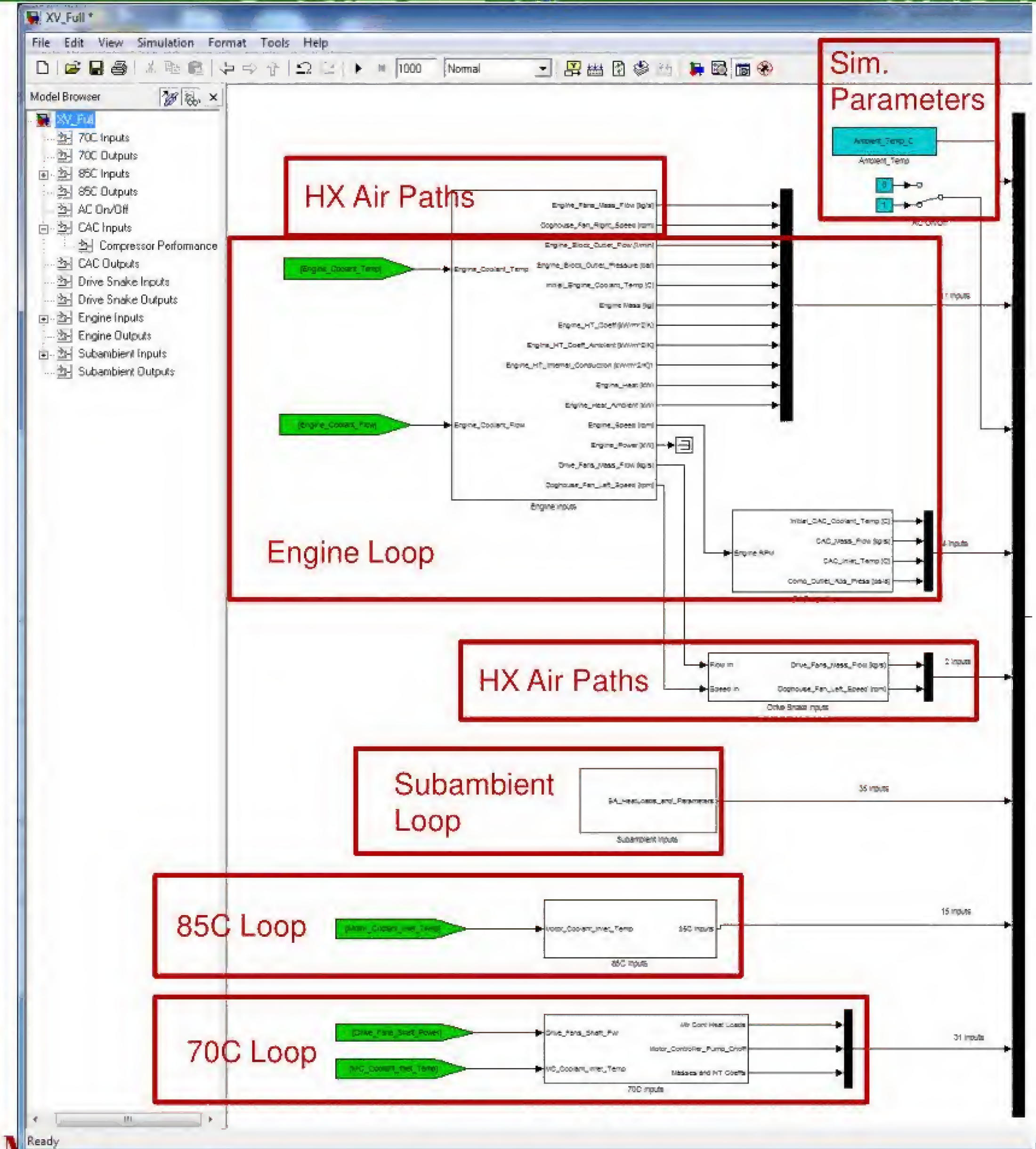
- **Model used for all airside and liquid circuits for cooling system**
- **Thermal and power inputs loaded via Heatloads.m from PAResults.csv**
- **Other inputs hard coded in Heatloads.m**

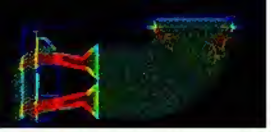




XV Simulink Model – Inputs







XV Simulink Model – Inputs to KULI

Key
Engine Loop
CAC Loop
Fans
SA 134a Loop
SA EGW Loop
85C Loop
70C Loop

In for KULI	
Ambient_Temp_C	C
Engine_Fans_Mass_Flow	kg/s
Doghouse_Fan_Right_Speed	1/min
Engine_Block_Outlet_Flow	l/min
Engine_Block_Outlet_Pressure	bar
Initial_Engine_Coolant_Temp	C
Engine_Mass	kg
Engine_HT_Coeff	kW/m^2/K
Engine_HT_Coeff_Ambient	kW/m^2/K
Engine_Internal_Conduction	W/m/K
Engine_Heat	kW
Engine_Heat_Ambient	kW
AC_Onoff	untransformec
Initial_CAC_Coolant_Temp	C
CAC_Mass_Flow	kg/s
CAC_Inlet_Temp	C
Comp_Outlet_Abs_Press	psi
Drive_Fans_Mass_Flow	kg/s
Doghouse_Fan_Left_Speed	1/min
PFC_Length	mm
AC_Comp_Speed	1/min
Battery1_Heat	kW
Battery2_Heat	kW
Battery1_Ambient_Heat	kW
Battery2_Ambient_Heat	kW
HV_Box_Heat	kW
HV_Box_Ambient_Heat	kW
LV_Box_Heat	kW
LV_Box_Ambient_Heat	kW
Turret_Heat	kW
Turret_Ambient_Heat	kW
Cont1_Heat	kW
Cont1_Ambient_Heat	kW
Cont2_Heat	kW
Cont2_Ambient_Heat	kW
SA_Main_Line_Dia	mm
Batt_Line_Dia_mm	mm
HLV_Line_Dia_mm	mm
Cont_Line_Dia_mm	mm
SA_PGW_Temp_CMD	C
Battery1_SCFM	ft^3/min
Battery2_SCFM	ft^3/min
HV_Box_SCFM	ft^3/min
LV_Box_SCFM	ft^3/min
Turret_SCFM	ft^3/min
SA_PGW_Pump_Onoff	1/min

In for KULI	
Motor_Heat_LF	kW
Motor_Heat_LM	kW
Motor_Heat_LR	kW
Motor_Heat_RF	kW
Motor_Heat_RM	kW
Motor_Heat_RR	kW
Generator1_Heat	kW
Motor_Pump_Onoff	1/min
Initial_Motor_Coolant_Temp	C
Motor_Mass	kg
Generator1_Mass	kg
Motor_HT_Coeff	kW/m^2/K
Generator1_HT_Coeff	kW/m^2/K
Mtr_Line_Dia_mm	mm
Gen_Line_Dia_mm	mm
Motor_Controller_Heat_LF	kW
Motor_Controller_Heat_LM	kW
Motor_Controller_Heat_LR	kW
Motor_Controller_Heat_RF	kW
Motor_Controller_Heat_RM	kW
Motor_Controller_Heat_RR	kW
Generator1_Controller_Heat	kW
Generator2_Heat	kW
Generator2_Controller_Heat	kW
DCDC1_1_Heat	kW
DCDC1_2_Heat	kW
LVDCDC_1_Heat	kW
LVDCDC_2_Heat	kW
LVDCDC_3_Heat	kW
Brake_Cont_1_Heat	kW
Brake_Cont_2_Heat	kW
DriveFanMotor_MandC_Heat	kW
Motor_Controller_Pump_Onoff	1/min
Initial_Controller_Coolant_Temp	C
Motor_Controller_Mass	kg
Generator1_Controller_Mass	kg
MV_Generator2_Mass	kg
MV_Generator2_Controller_Mas	kg
DCDC1_Mass	kg
LVDCDC_Mass	kg
Motor_Controller_HT_Coeff	kW/m^2/K
MV_Gen2_HT_Coeff	kW/m^2/K
MV_Gen2_Cont_HT_Coeff	kW/m^2/K
DCDC1_HT_Coeff	kW/m^2/K
LVDCDC_HT_Coeff	kW/m^2/K
Initial_Gen2_Coolant_Temp	C

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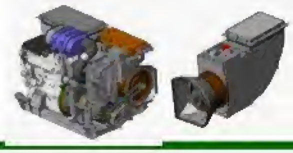
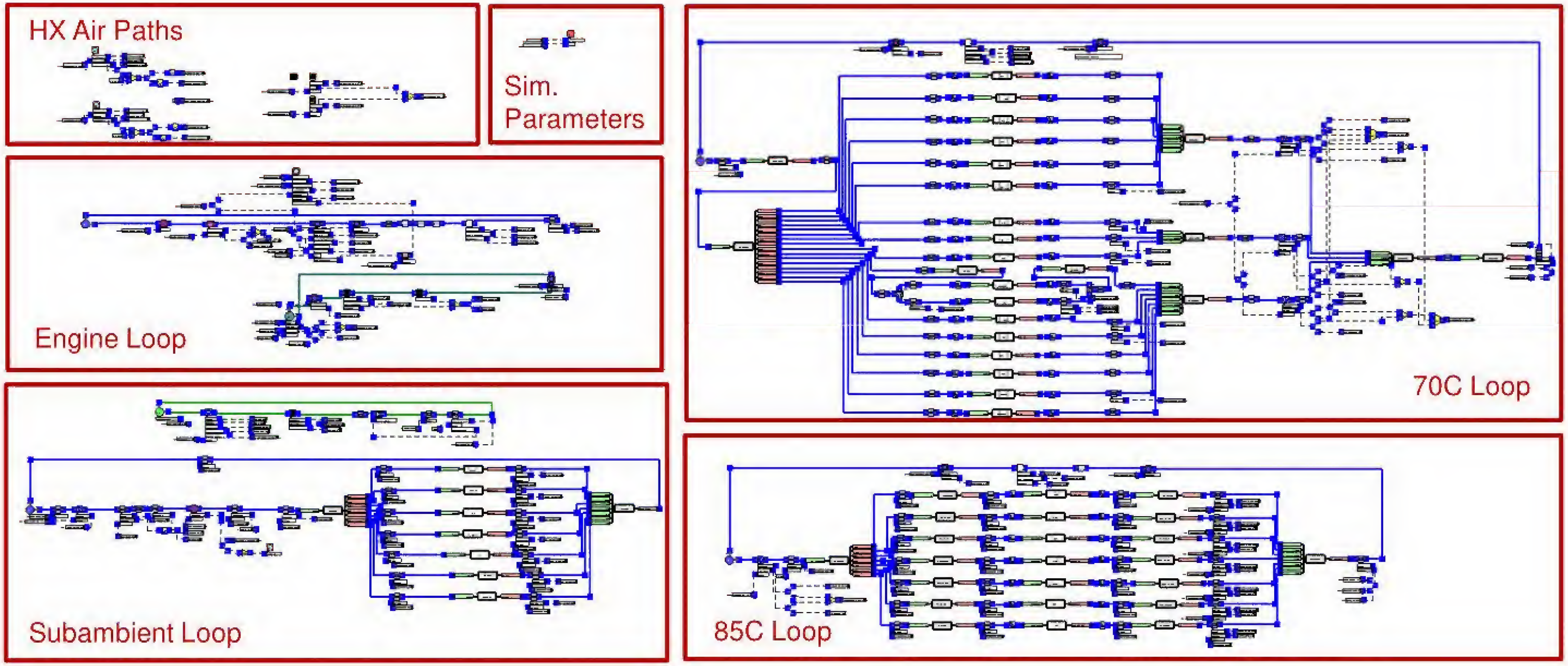
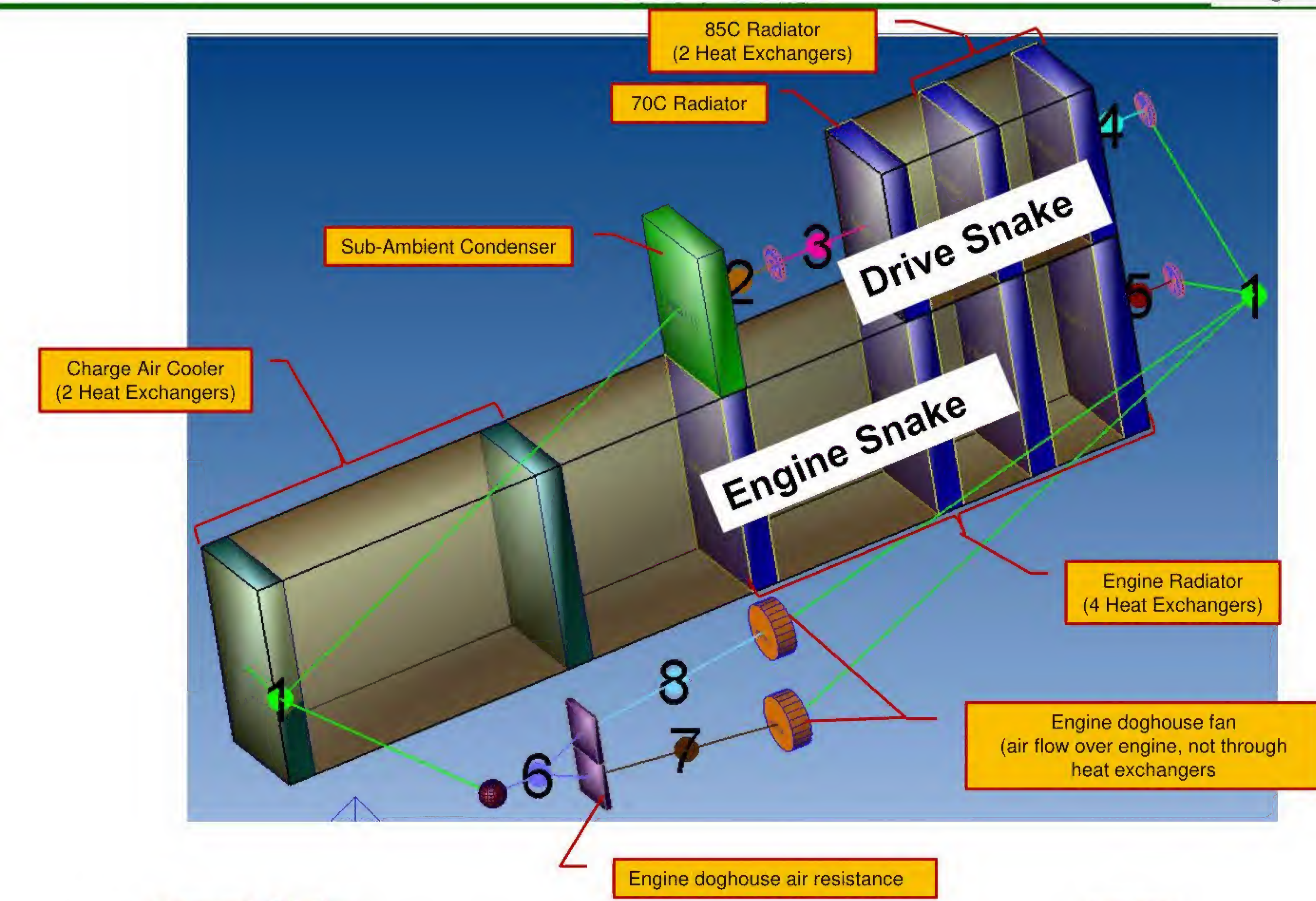
XV KULI Model – Coolant Loop Sections

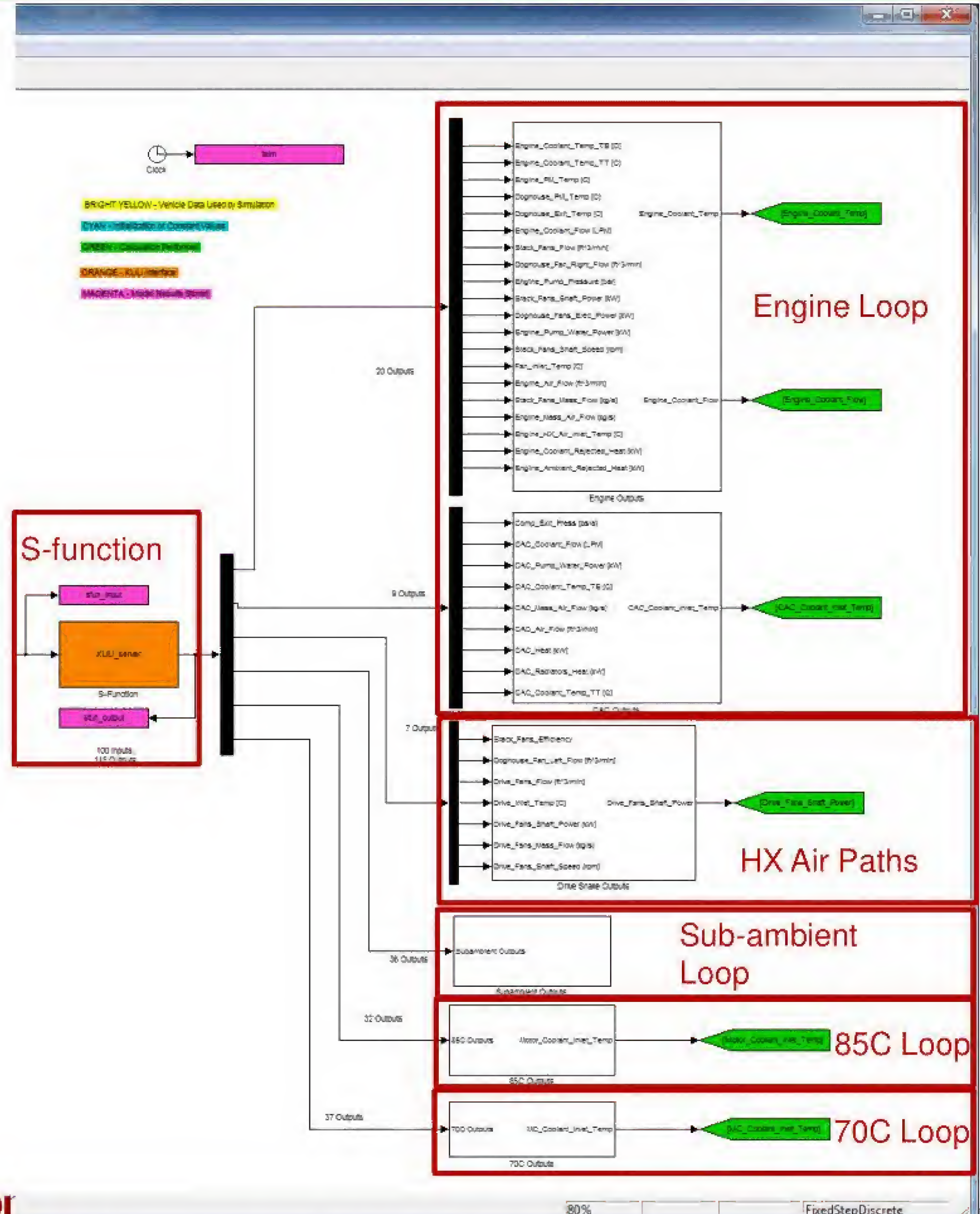


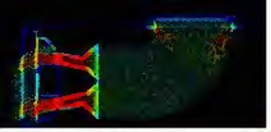


XV KULI Model – Air Paths



XV Simulink Model – Outputs





XV Simulink Model – Outputs

Key
Engine Loop
CAC Loop
Fans
SA 134a Loop
SA EGW Loop
85C Loop
70C Loop

Out of KULI	
Engine_Coolant_Temp_TB	C
Engine_Coolant_Temp_TT	C
Engine_PM_Temp	C
Doghouse_PM_Temp	C
Doghouse_Exit_Temp	C
Engine_Coolant_Flow	l/min
Stack_Fans_Flow	ft^3/min
Doghouse_Fan_Right_Flow	ft^3/min
Engine_Pump_Pressure	bar
Stack_Fans_Shaft_Power	kW
Doghouse_Fans_Elec_Power	kW
Engine_Pump_Water_Power	kW
Stack_Fans_Shaft_Speed	1/min
Fan_Inlet_Temp	C
Engine_Air_Flow	ft^3/min
Stack_Fans_Mass_Flow	kg/s
Engine_Mass_Air_Flow	kg/s
Engine_HX_Air_Inlet_Temp	C
Engine_Coolant_Rejected_Heat	kW
Engine_Ambient_Rejected_Heat	kW
Comp_Exit_Press	psi
CAC_Coolant_Flow	l/min
CAC_Pump_Water_Power	kW
CAC_Coolant_Temp_TB	C
CAC_Mass_Air_Flow	kg/s
CAC_Air_Flow	ft^3/min
CAC_Heat	kW
CAC_Radiators_Heat	kW
CAC_Coolant_Temp_TT	C
Stack_Fans_Efficiency	untransformed
Doghouse_Fan_Left_Flow	ft^3/min
Drive_Fans_Flow	ft^3/min
Drive_Inlet_Temp	C
Drive_Fans_Shaft_Power	kW
Drive_Fans_Mass_Flow	kg/s
Drive_Fans_Shaft_Speed	1/min
SA_Cond_Heat	kW
AC_Balanced	untransformed
SA_Comp_Power	kW
SA_Cond_Temp	C
SA_Cond_Temp_Out	C
SA_Evap_Temp_Out	C
Comp_Pin	psi
Comp_Pout	psi
Comp_Mass_Flow	kg/s
SA_Comp_Power_2_Refrigerant	kW

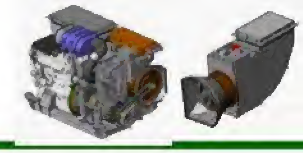
Out of KULI	
SA_PGW_Temp	C
SA_PGW_Temp_Target_Heat	kW
Battery1_Air_Temp_Out	C
Battery1_Air_Temp_In	C
Battery2_Air_Temp_Out	C
Battery2_Air_Temp_In	C
HV_Box_Air_Temp_Out	C
HV_Box_Air_Temp_In	C
LV_Box_Air_Temp_Out	C
LV_Box_Air_Temp_In	C
Turret_Air_Temp_Out	C
Turret_Air_Temp_In	C
Cont1_Temp	C
Cont2_Temp	C
SA_PGW_GPM	US GPM
Battery1_GPM	US GPM
Battery2_GPM	US GPM
HV_Box_GPM	US GPM
LV_Box_GPM	US GPM
Turret_GPM	US GPM
Cont1_GPM	US GPM
Cont2_GPM	US GPM
BPHX_Temp_In	C
BPHX_dP_Act	psi
BPHX_Temp_Out	C
M_Coolant_Temp_TT	C
M_Coolant_Flow	l/min
M_Air_Flow	ft^3/min
M_Coolant_Heat	kW
M_Coolant_Temp_TB	C
Motor_Pump_Water_Power	kW
LF_Coolant_Flow	US GPM
LM_Coolant_Flow	US GPM
LR_Coolant_Flow	US GPM
RF_Coolant_Flow	US GPM
RM_Coolant_Flow	US GPM
RR_Coolant_Flow	US GPM
G1_Coolant_Flow	US GPM
LF_Coolant_Temp	C
LM_Coolant_Temp	C
LR_Coolant_Temp	C
RF_Coolant_Temp	C
RM_Coolant_Temp	C
RR_Coolant_Temp	C
G1_Coolant_Temp	C
M_Coolant_Exit_Temp	C

Out of KULI	
LF_Motor_Temp	C
LM_Motor_Temp	C
LR_Motor_Temp	C
RF_Motor_Temp	C
RM_Motor_Temp	C
RR_Motor_Temp	C
G1_Temp	C
M_Mass_Air_Flow	kg/s
M_Coolant_Inlet_Temp	C
Motor_Pump_Flow	US GPM
Motor_Pump_dP	psi
MC_Coolant_Temp_TT	C
MC_Coolant_Flow	l/min
MC_Rad_Inlet_Air_Temp	C
MC_Coolant_Heat	kW
MC_Air_Flow	ft^3/min
MC_Coolant_Temp_TB	C
Controller_Pump_Water_Power	kW
G2_Coolant_Flow	l/min
G2_Cont_Coolant_Flow	l/min
G2_Coolant_Temp	C
MC_Coolant_Exit_Temp	C
G2_Temp	C
LF_Cont_Temp	C
LM_Cont_Temp	C
LR_Cont_Temp	C
RF_Cont_Temp	C
RM_Cont_Temp	C
RR_Cont_Temp	C
G1_Cont_Temp	C
G2_Cont_Temp	C
MC_Mass_Air_Flow	kg/s
MC_Coolant_Inlet_Temp	C
G2_Coolant_Inlet_Temp	C
DCDC1_1_Coolant_Flow	l/min
LVDCDC_1_Coolant_Flow	l/min
G1_Controller_Coolant_Flow	l/min
RR_Controller_Coolant_Flow	l/min
Brake_Cont_1_Coolant_Flow	l/min
Controller_Pump_1_Flow	US GPM
Controller_Pump_1_dP	psi
Controller_Pump_2_Flow	US GPM
Controller_Pump_2_dP	psi
Controller_Pump_3_Flow	US GPM
Controller_Pump_3_dP	psi
Controller_Pumps_Flow	US GPM
DriveFanMotor_Coolant_Flow	l/min
DCDC1_2_Coolant_Flow	l/min

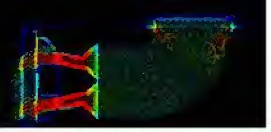
XV KULI Model Overview – Simulation Parameters and Cases

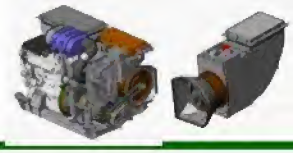
- Ambient temperature = 45C
- Ambient air pressure = 1013hPa
- Simulation time step = 1 sec
- Simulation run time = 1000 sec
- Other heat loads can be developed
  - → Data saved using the same PAResults file structure approach
  - → PAResults can be added to Heatloads.m
  - → Run Simulink

Conclusion

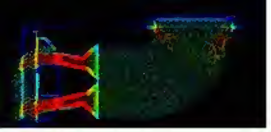


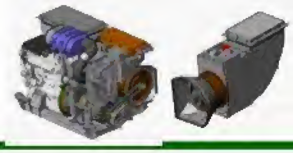
- Steady state thermal loads and power for three stressing cases (PAResults.csv) included
  - → 80 kph, flat, pavement (1)
  - → 45 kph, flat, dirt (2)
  - → 5 kph, 60% grade, pavement (3)
- Simulink/Matlab output
  - → Additional scopes can be added to monitor variables
  - → Other controls can be added – monitor temperatures and control compressor, pump, and fan flow rates
- The following slides are present the details of the thermal model. They can be used to develop a thermal model in a software package other than Kuli.



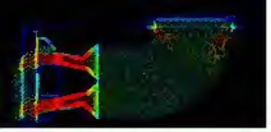


Engine Snake Details

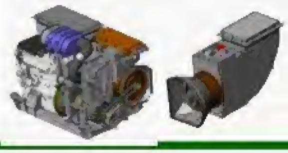




Engine EGW Loop

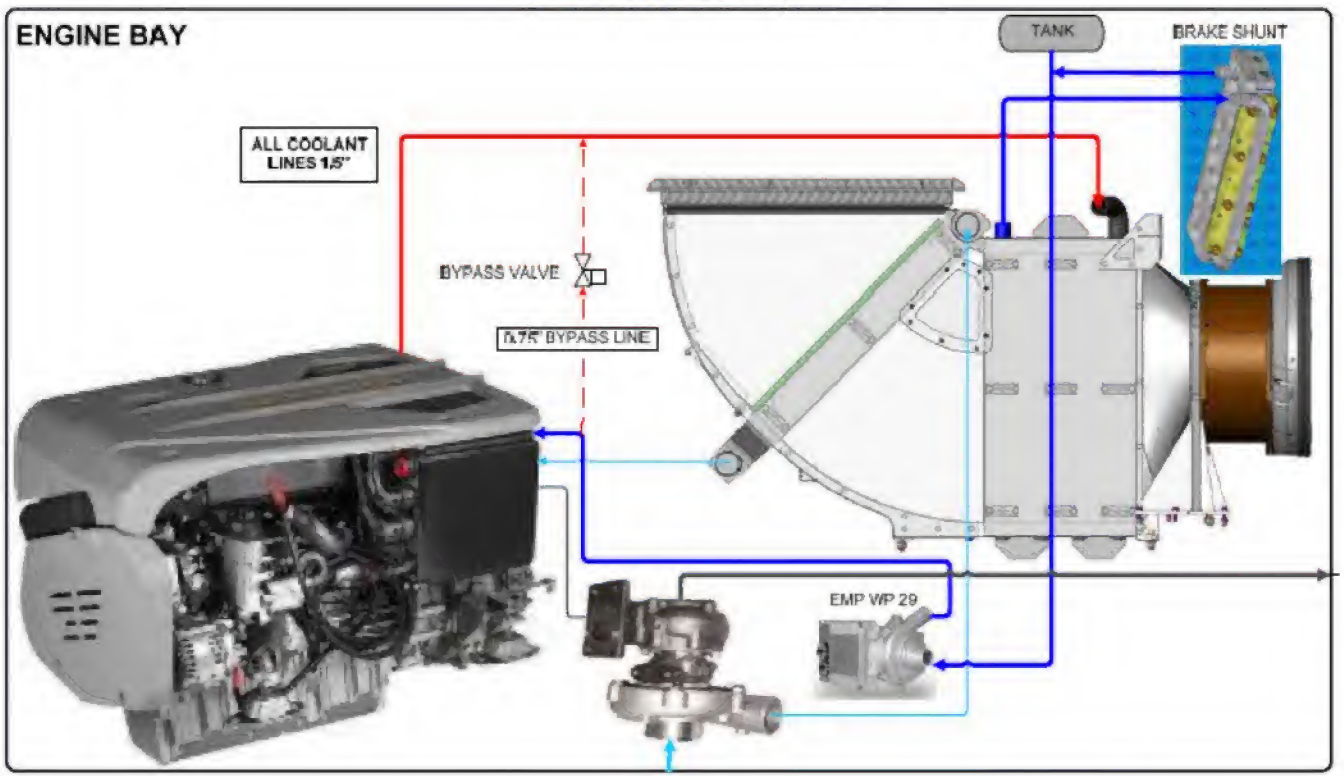


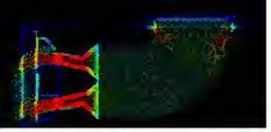
XV – Engine Loop



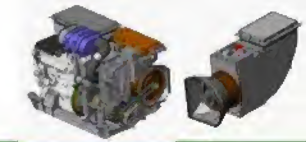
- **CAC and EGW heat exchangers in Engine Snake**
- **Shunt cooling when engine off - Bypass valve and electric pump used in lieu of engine water pump**

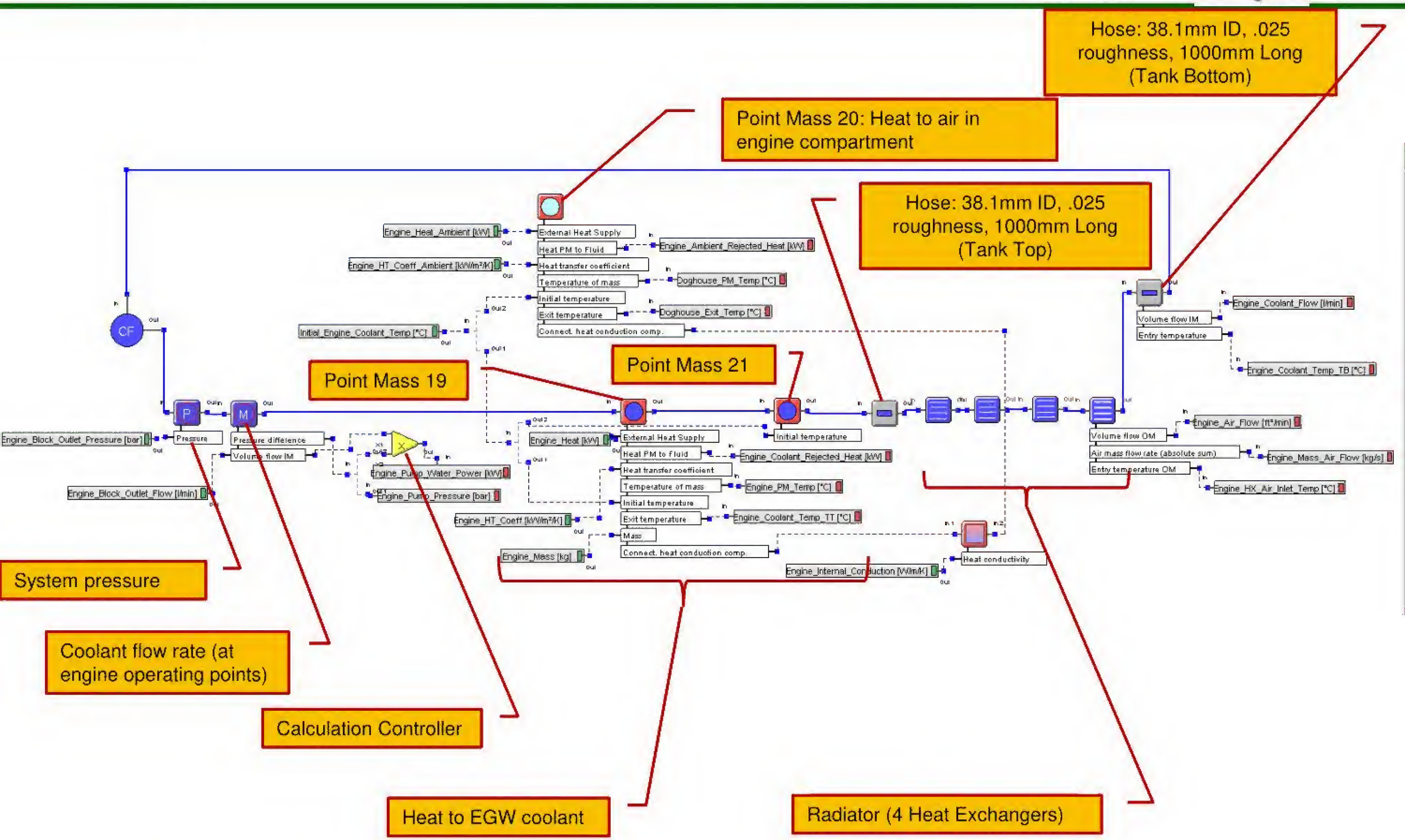
ENGINE COOLING LOOP



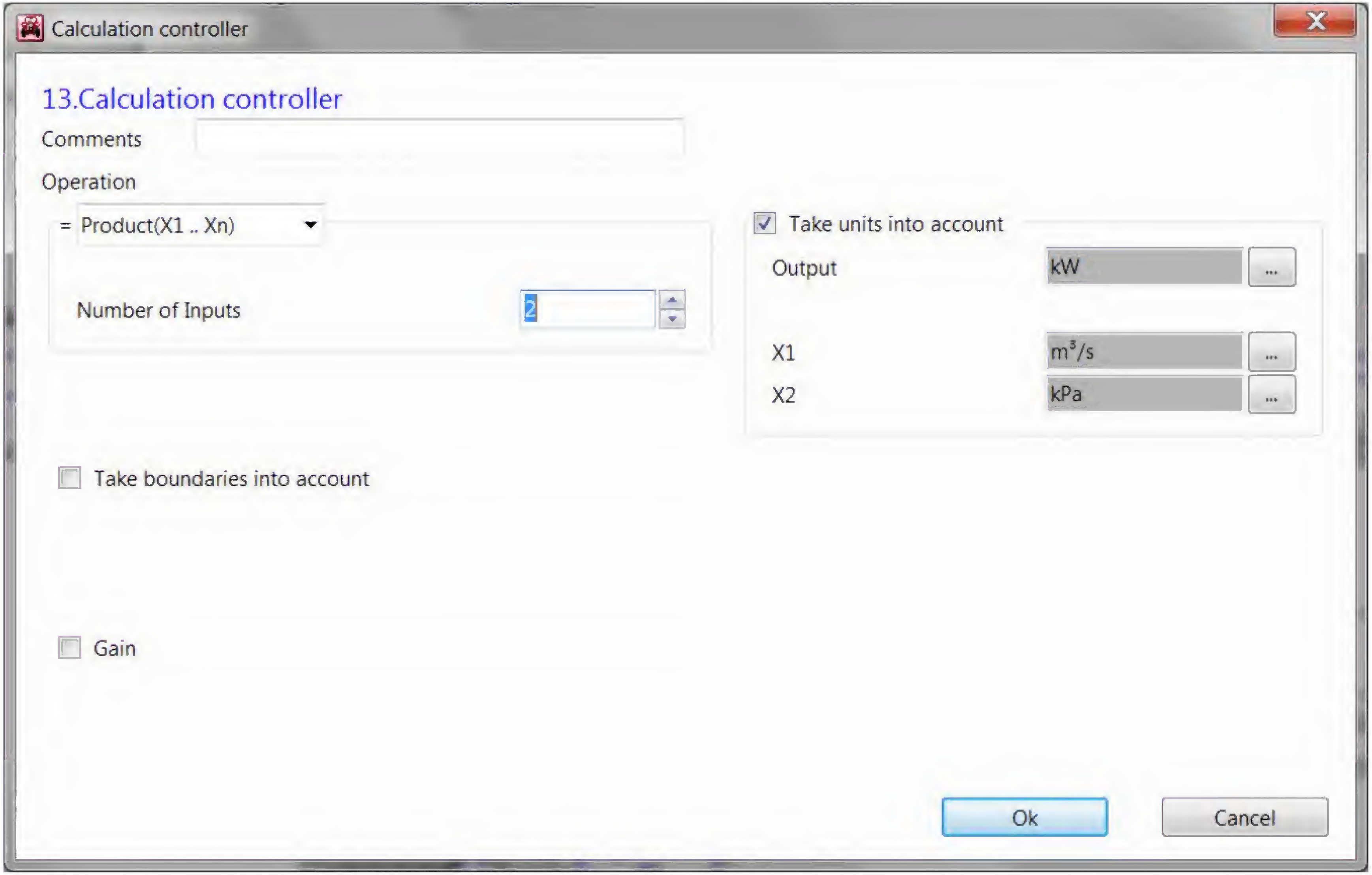


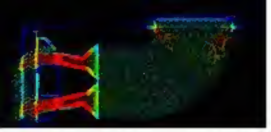
Kuli Engine EGW Loop



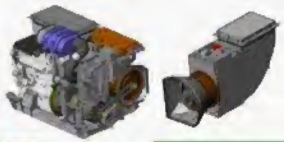


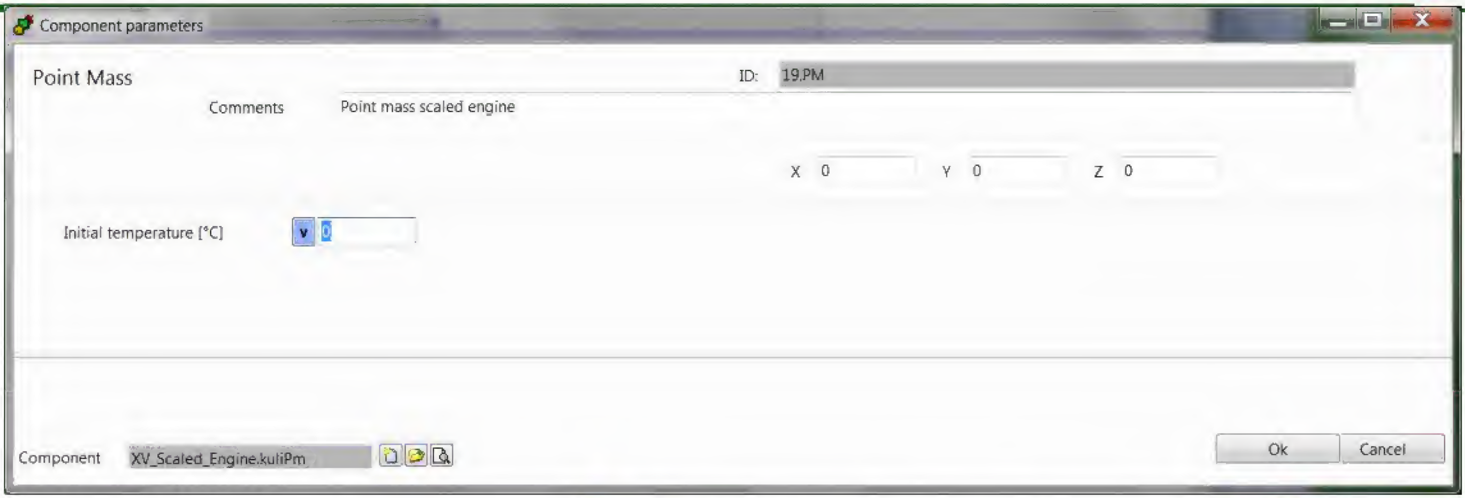
13.Calculation controller

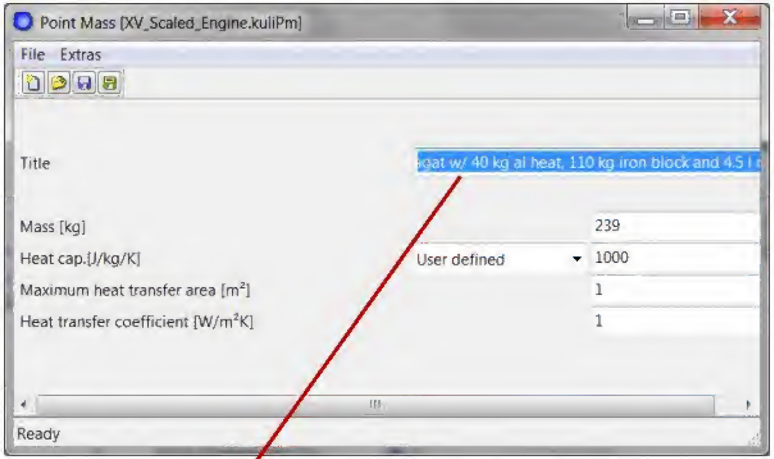




19.Point mass scaled engine







Scaled Engine - thermal mass is aggregate w/ 40 kg al heat, 110 kg iron block and 4.5 l oil

XV_Scaled_Engine.kuliPm

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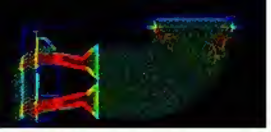
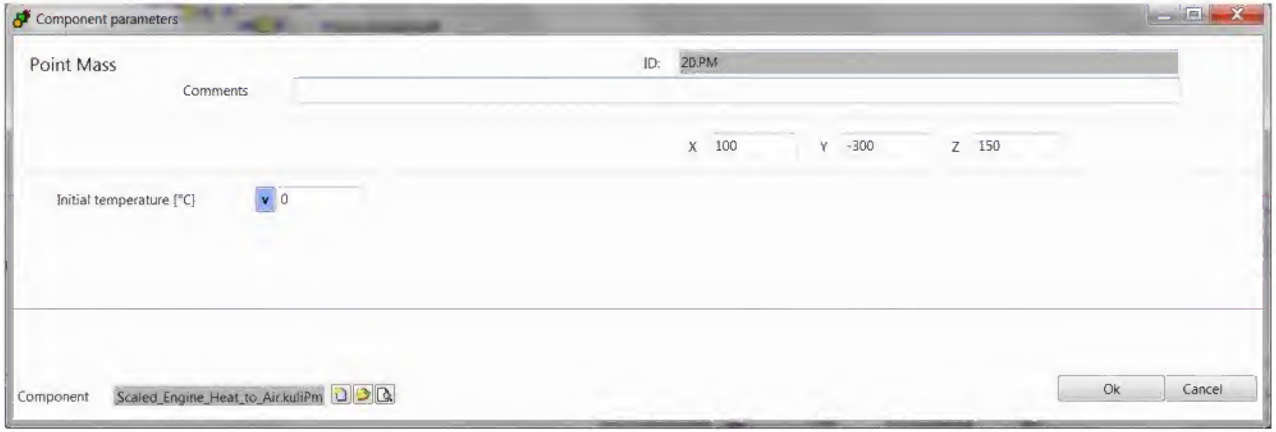
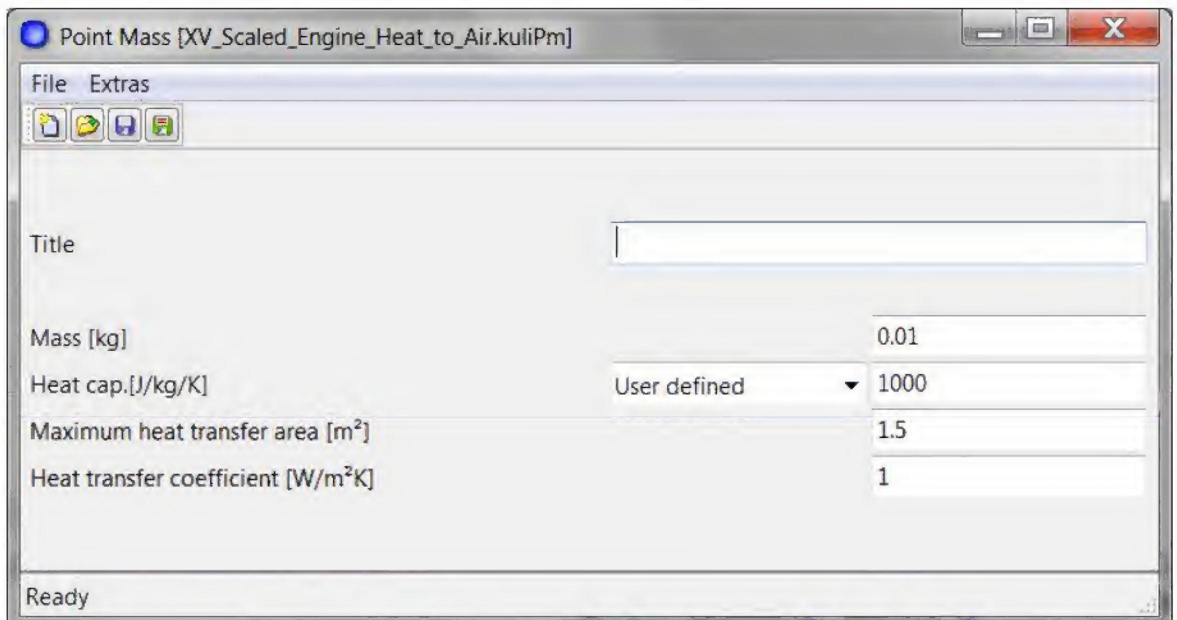
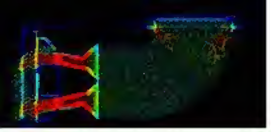


20.Point Mass

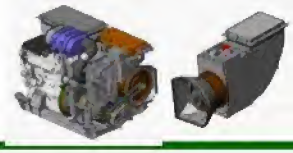


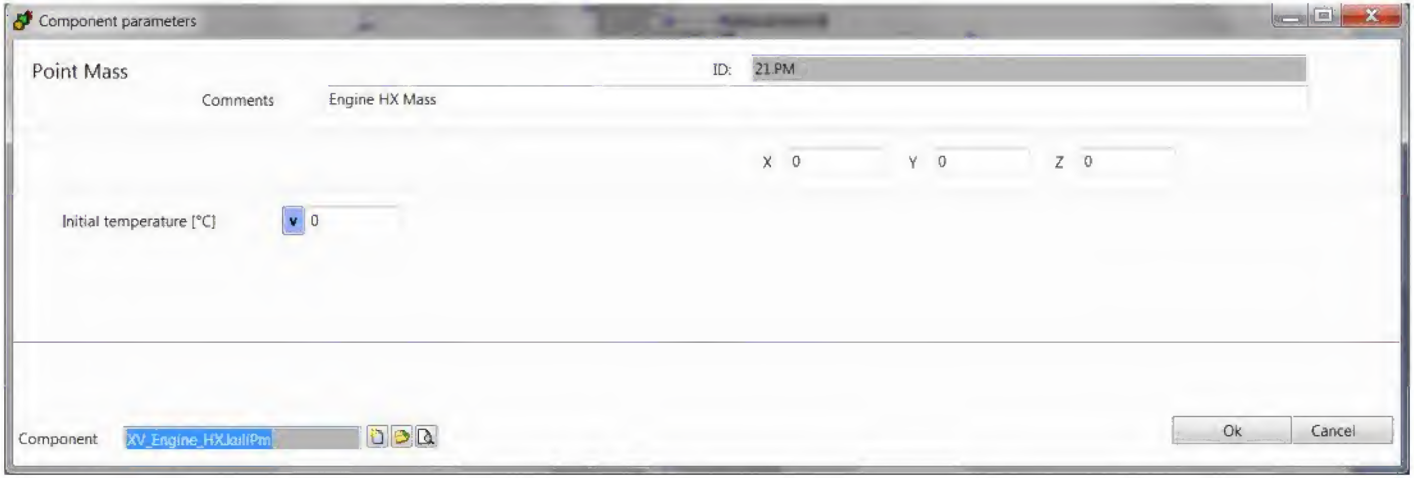


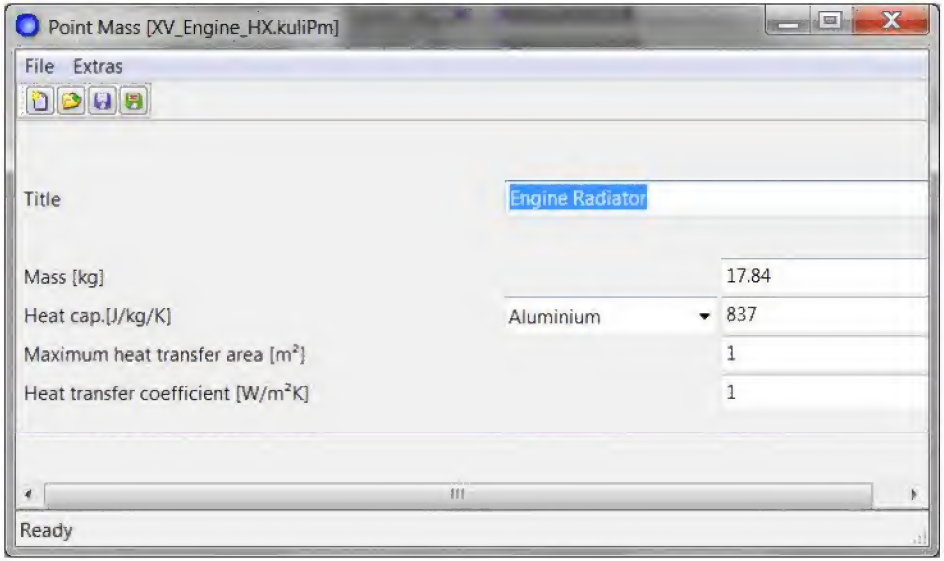
XV_Scaled_Engine_Heat_to_Air.kuliPm



21.Point mass engine HX mass







XV_Engine_HX.kuliPm

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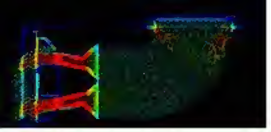
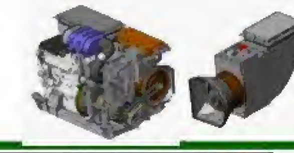
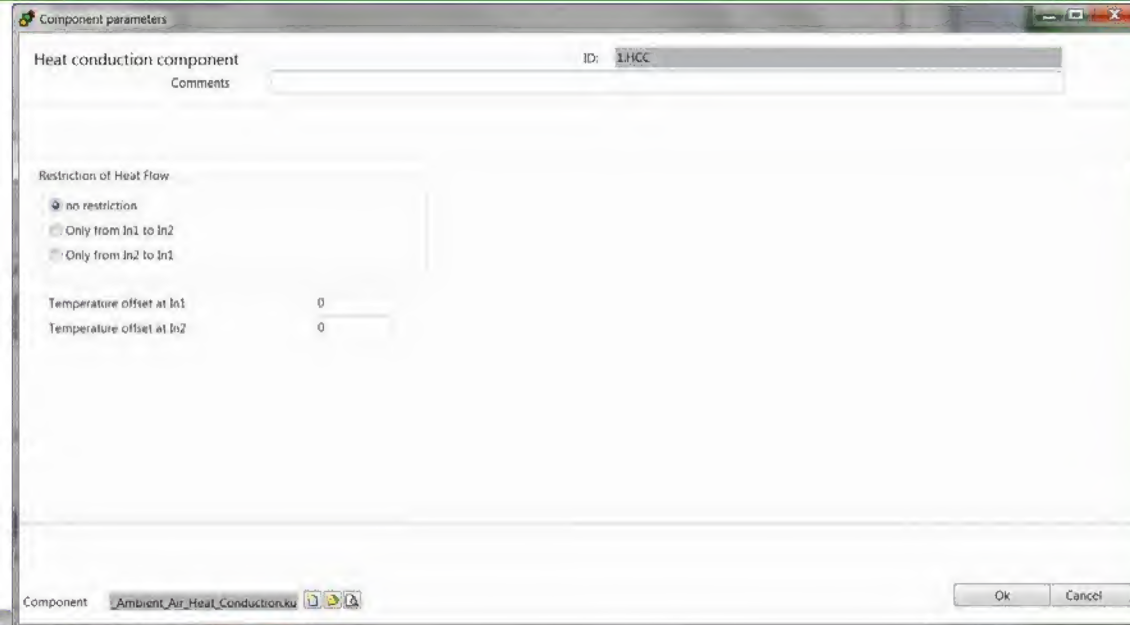
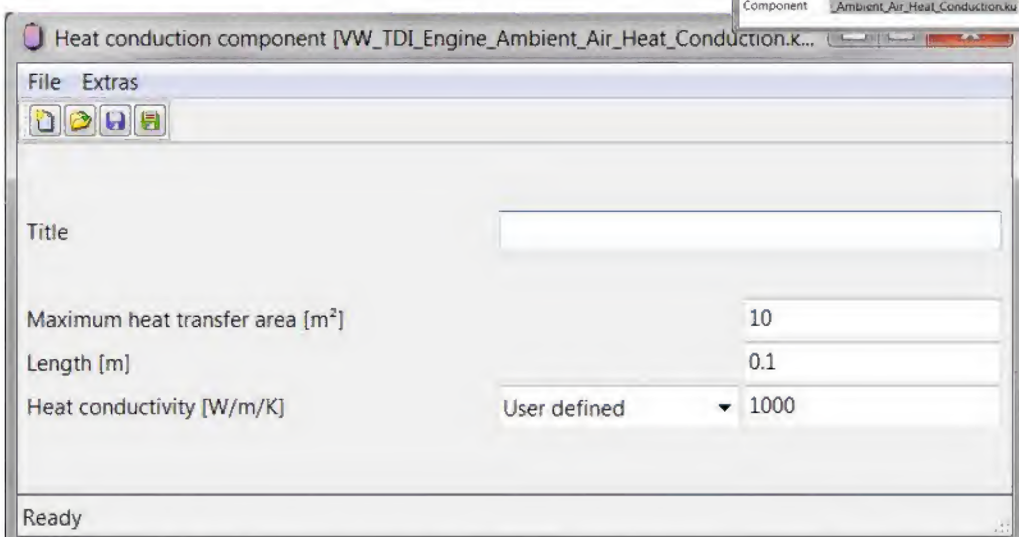


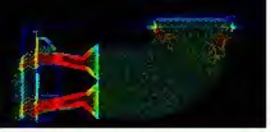
1.Heat conduction component

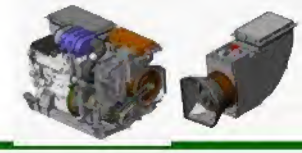




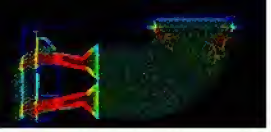


VW_TDI_Engine_Ambient_Air_Heat_Conduction.kuliDatHeat.kuliHcc

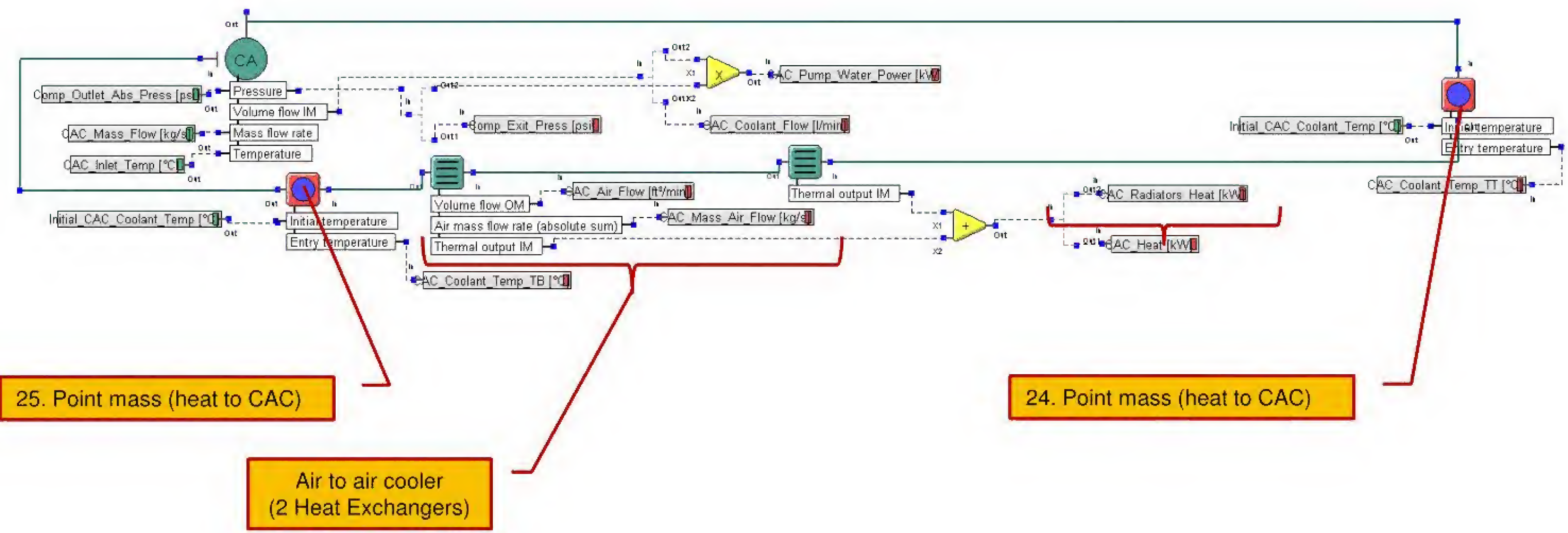


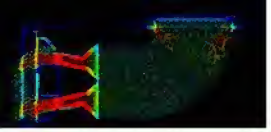


Engine Charge Air Cooler Loop

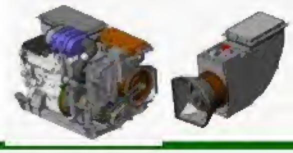


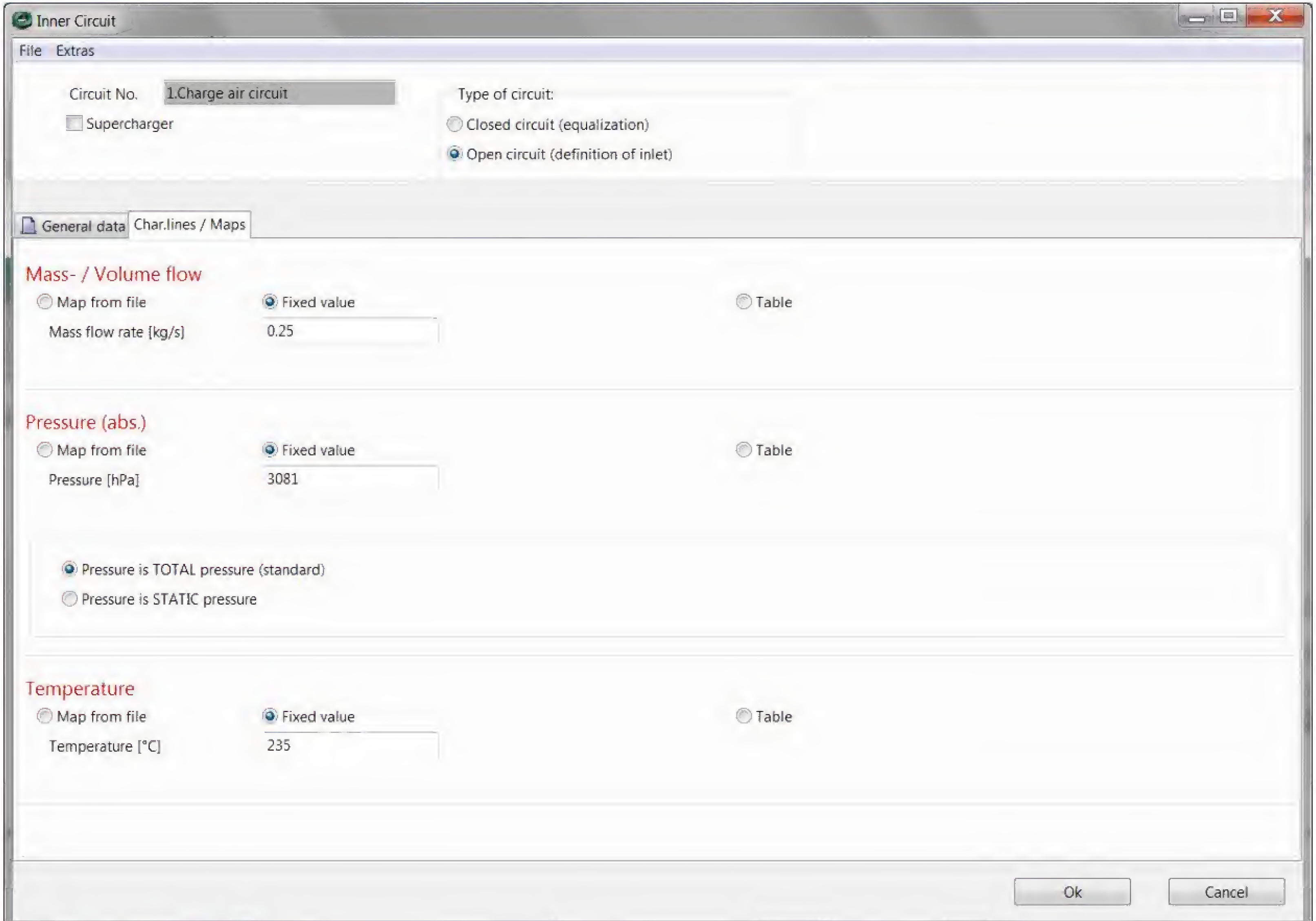
Kuli Engine Charge Air Cooler Loop

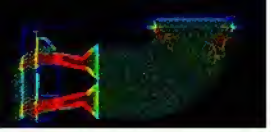




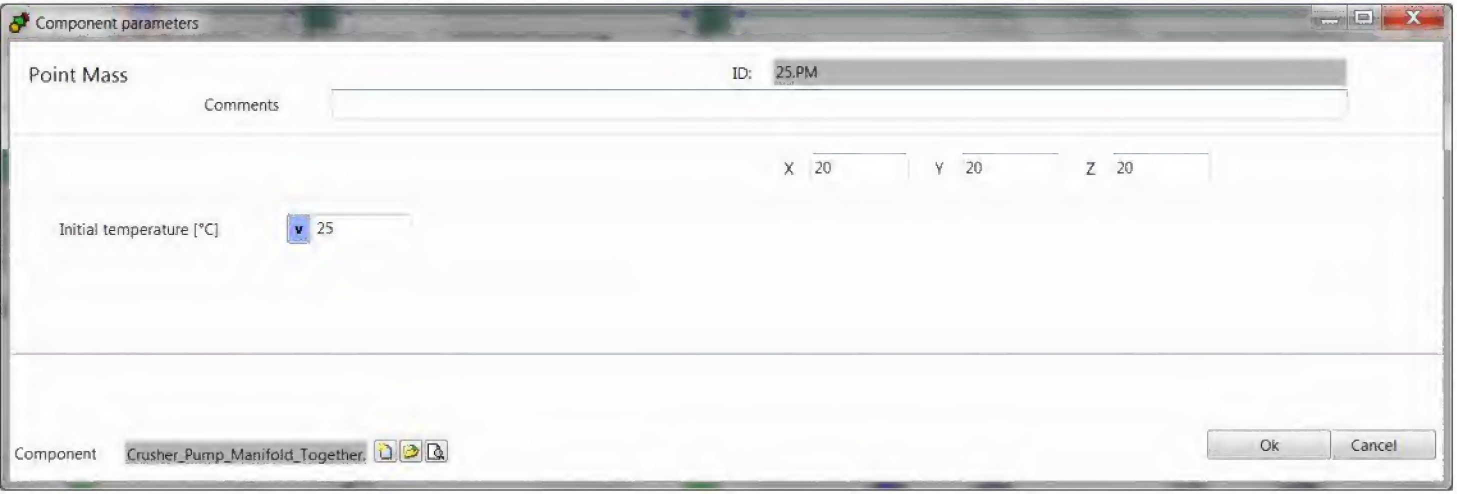
Charge Air Circuit: Component parameters

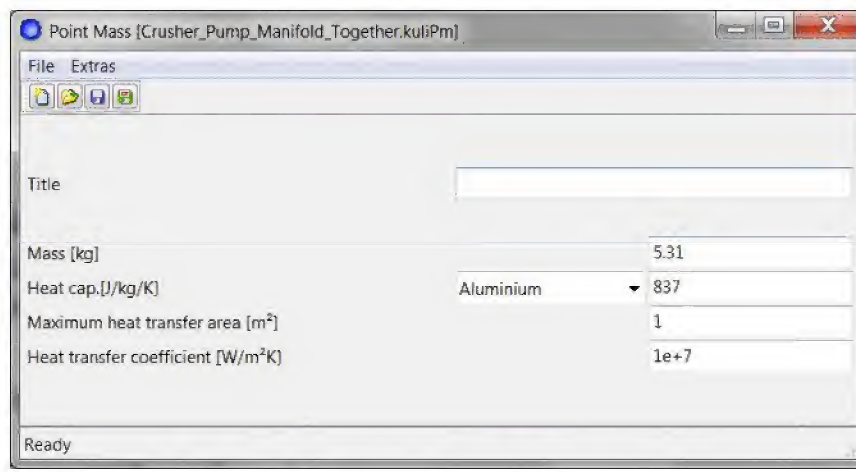




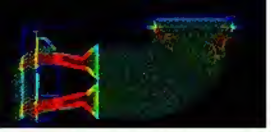


25.Point mass: Component parameters

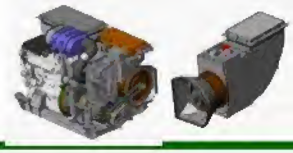


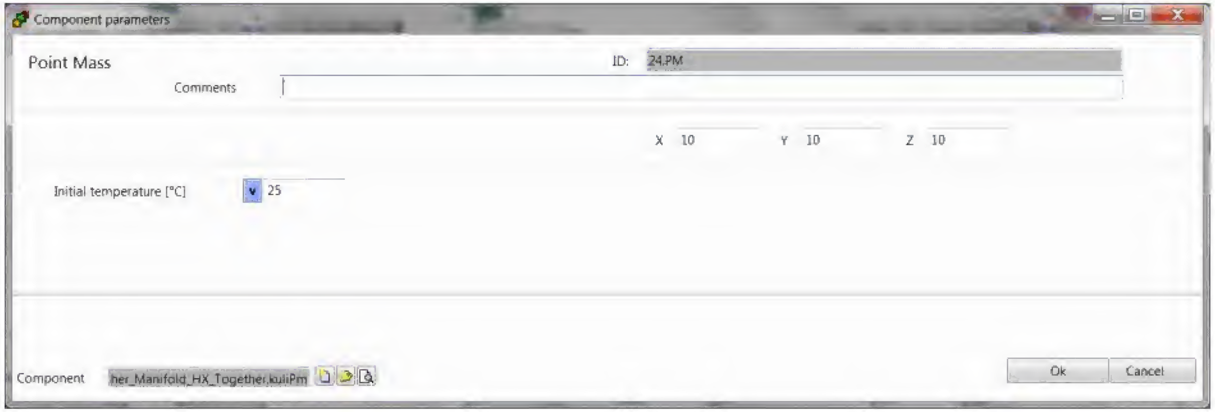


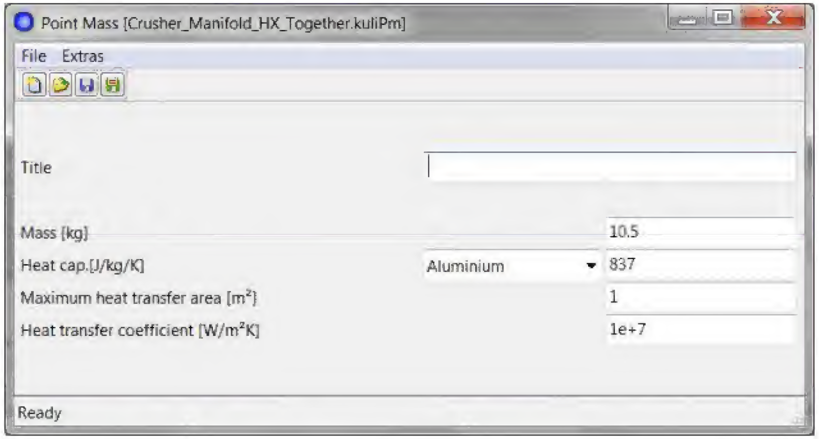
Crusher_Pump_Manifold_Together.kuliPm



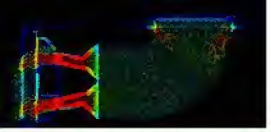
24.Point mass : Component parameters



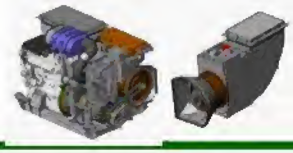


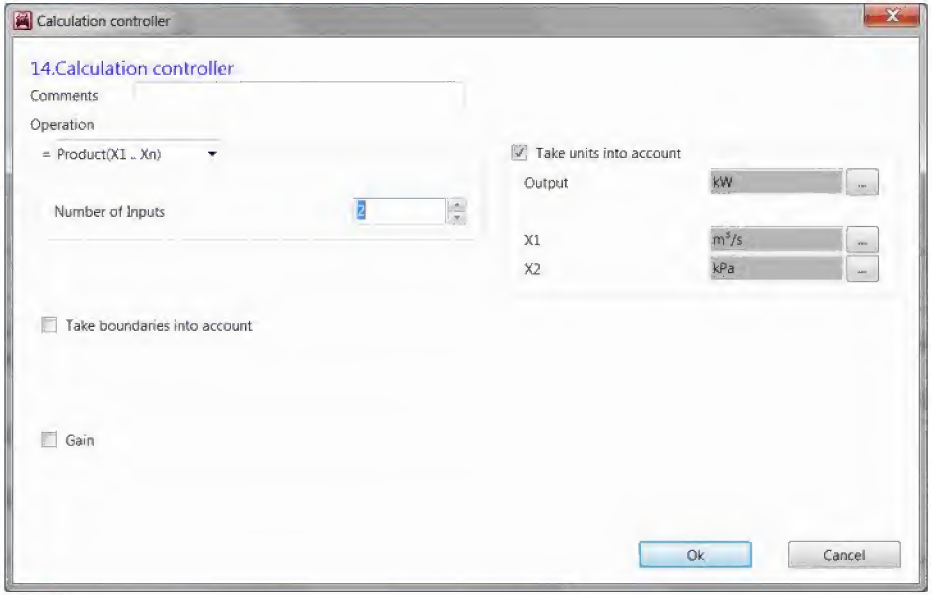


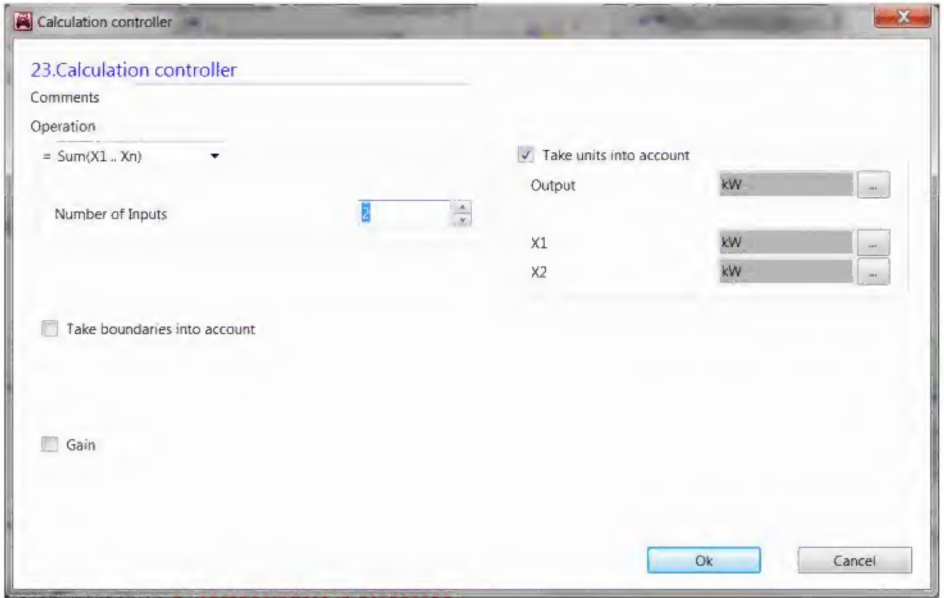
Crusher_Manifold_HX_Together.kuliPm

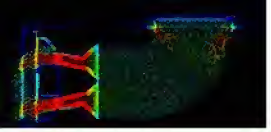


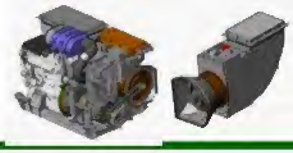
Calculation Controller: Component parameters



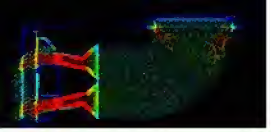




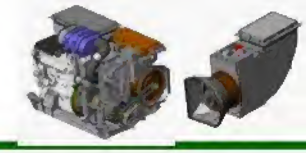


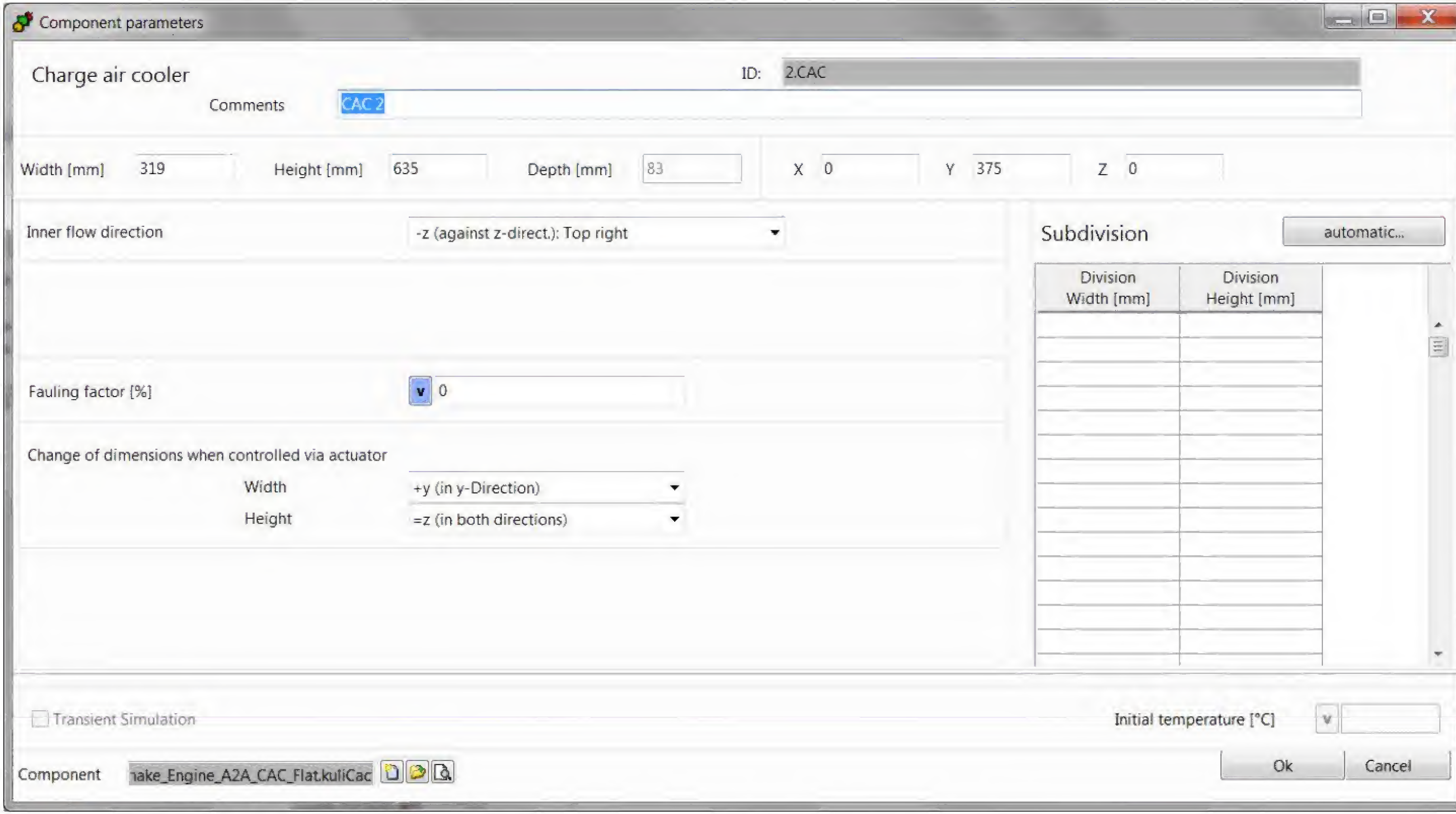


Charge Air Cooler Radiator Parameters

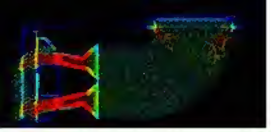


Charge Air Cooler (CAC) Parameters

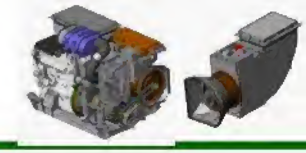


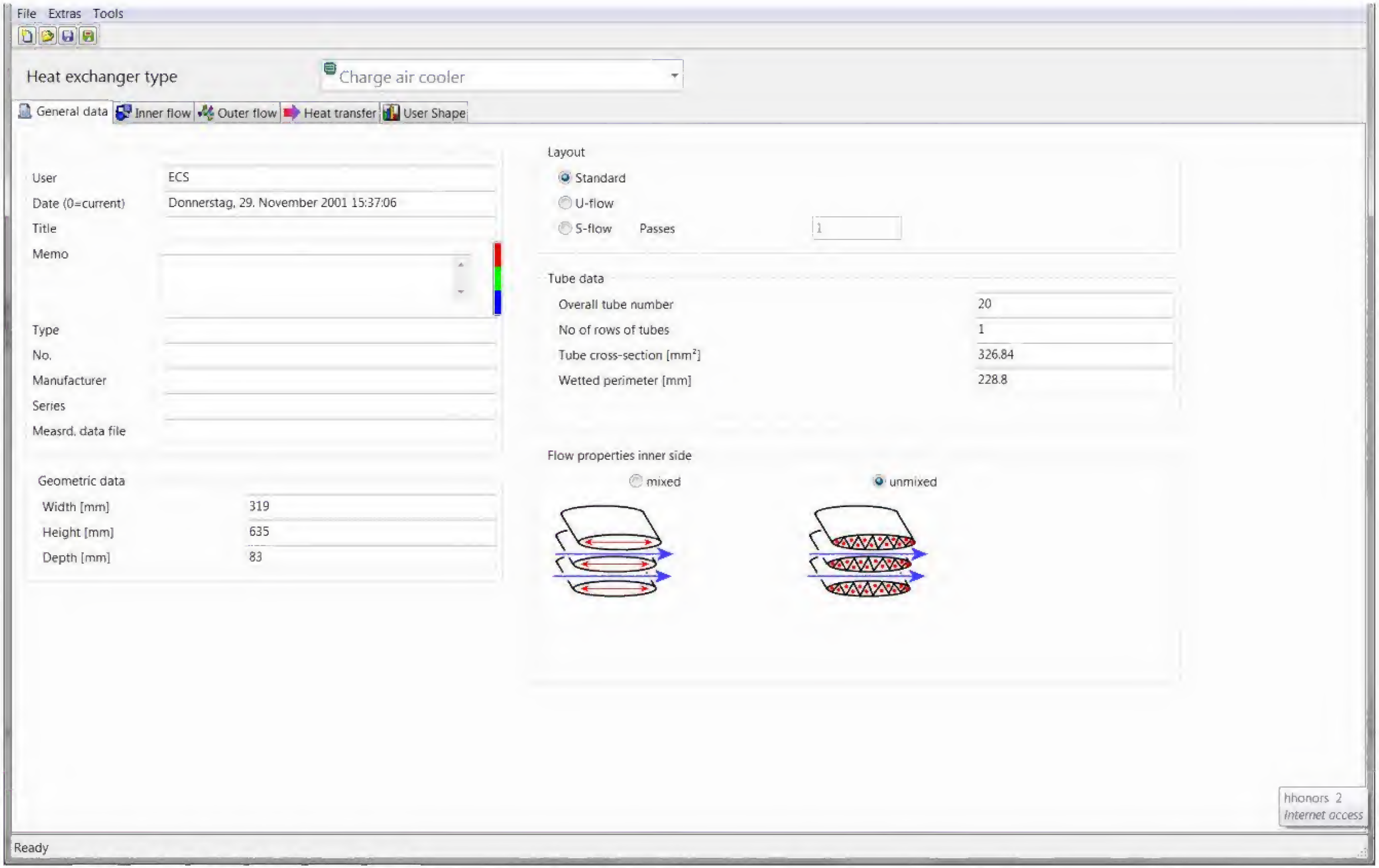


XV_Snake_Engine_A2A_CAC_Flat.kuliCac



Charge Air Cooler (CAC) Parameters





XV_Snake_Engine_A2A_CAC_Flat.kuliCac

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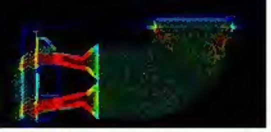
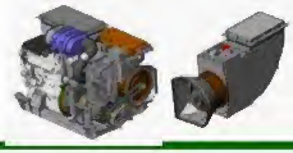
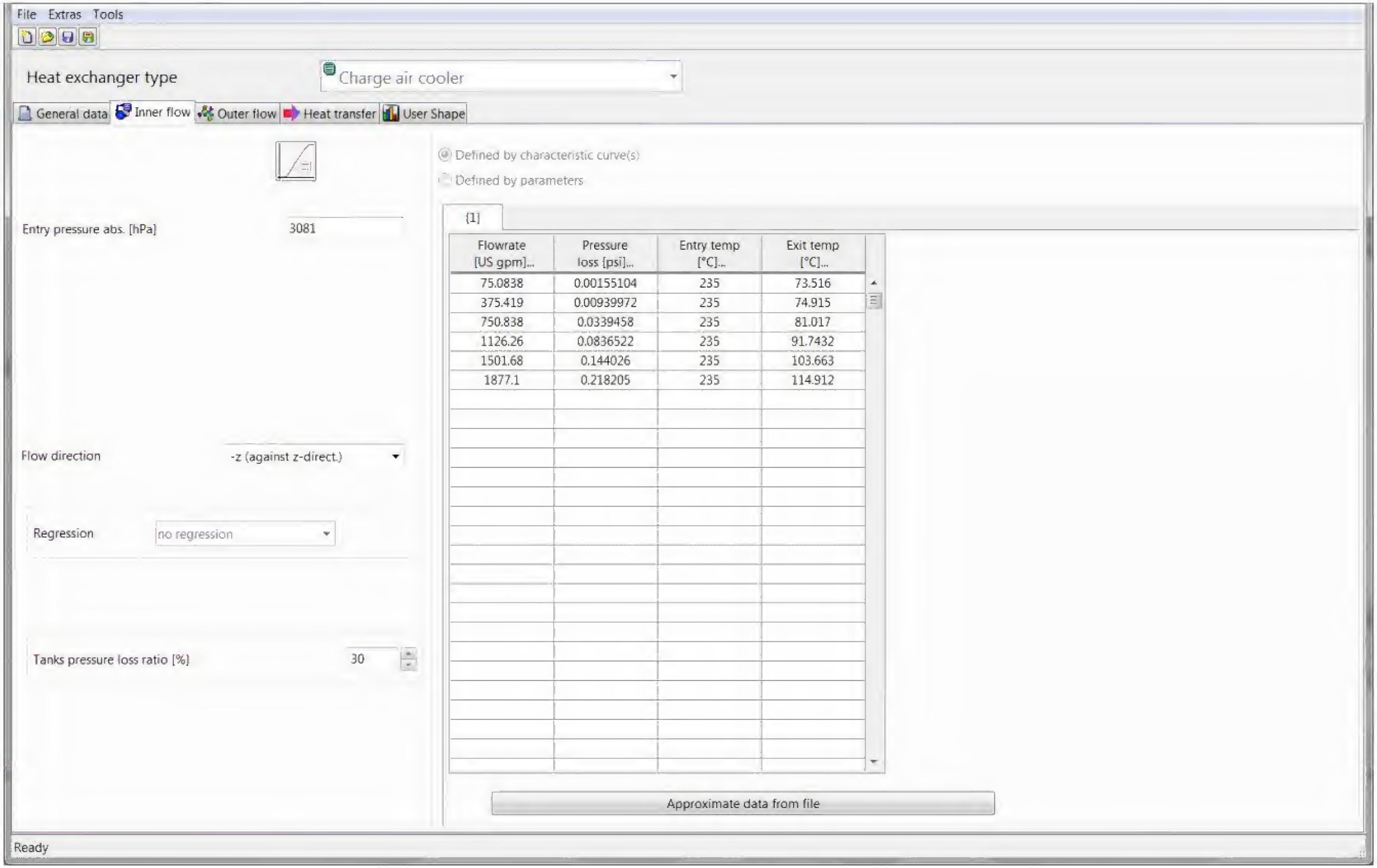


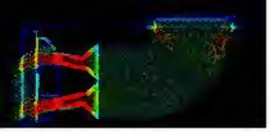
Charge Air Cooler (CAC) Parameters



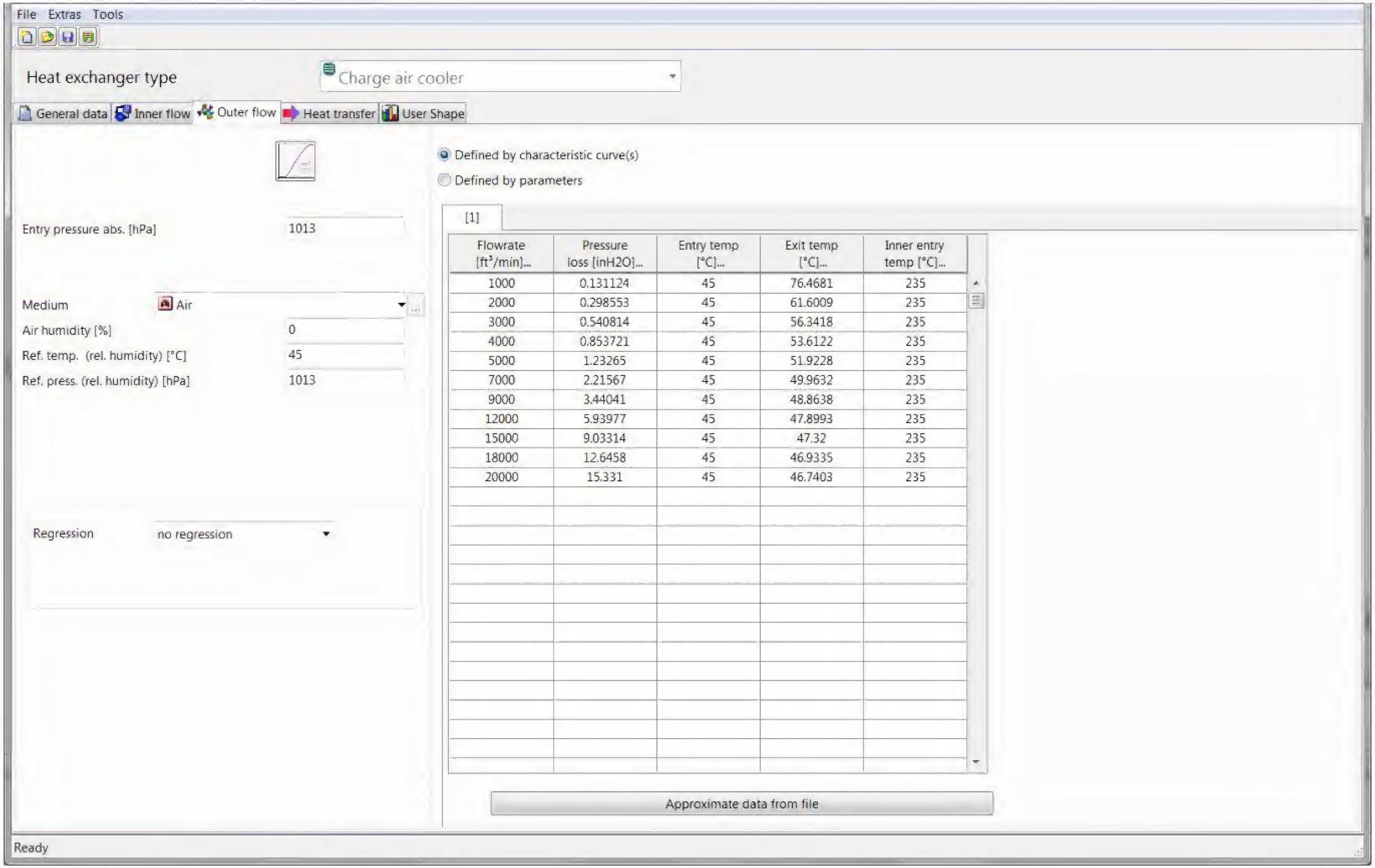


Flowrate [US gpm]...	Pressure loss [psi]...	Entry temp [°C]...	Exit temp [°C]...
75.0838	0.00155104	235	73.516
375.419	0.00939972	235	74.915
750.838	0.0339458	235	81.017
1126.26	0.0836522	235	91.7432
1501.68	0.144026	235	103.663
1877.1	0.218205	235	114.912

XV_Snake_Engine_A2A_CAC_Flat.kuliCac



Charge Air Cooler (CAC) Parameters



File Extras Tools

Heat exchanger type: Charge air cooler

General data | Inner flow | Outer flow | Heat transfer | User Shape

Entry pressure abs. [hPa]: 1013

Medium: Air

Air humidity [%]: 0

Ref. temp. (rel. humidity) [°C]: 45

Ref. press. (rel. humidity) [hPa]: 1013

Regression: no regression

(•) Defined by characteristic curve(s)

( ) Defined by parameters

[1]

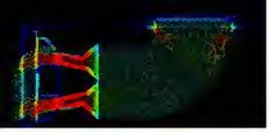
Flowrate [ft³/min]...	Pressure loss [inH2O]...	Entry temp [°C]...	Exit temp [°C]...	Inner entry temp [°C]...
1000	0.131124	45	76.4681	235
2000	0.298553	45	61.6009	235
3000	0.540814	45	56.3418	235
4000	0.853721	45	53.6122	235
5000	1.23265	45	51.9228	235
7000	2.21567	45	49.9632	235
9000	3.44041	45	48.8638	235
12000	5.93977	45	47.8993	235
15000	9.03314	45	47.32	235
18000	12.6458	45	46.9335	235
20000	15.331	45	46.7403	235

Approximate data from file

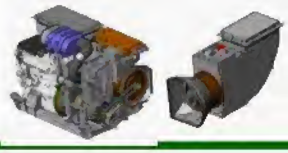
Ready

XV_Snake_Engine_A2A_CAC_Flat.kuliCac

NATIONAL ROBOTICS NREC ENGINEERING CENTER



Charge Air Cooler (CAC) Parameters



Charge air cooler [XV_Snake_Engine_A2A_CAC_Flat.kuliCac]

File Extras Tools

Heat exchanger type: Charge air cooler

General data | Inner flow | Outer flow | Heat transfer | User Shape

For visualisation, regression, extension or theoretical limits click the image

Heat definition by
- (•) Heat quantity
- ( ) Exit temperature inside
- ( ) Exit temperature outside

Diagram settings: Phi (P: inner mass flow)

☐ Theor. limits

Regression
(Phi (P: inner mass flow))
no regression

[1] [2] [3] [4] [5] [6]

Inner flow: US gpm
75.084

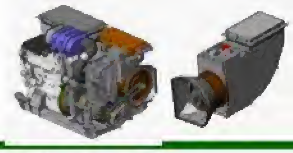
Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	1499.56	45	235	---
2000	1499.67	45	235	---
3000	1499.71	45	235	---
4000	1499.74	45	235	---
5000	1499.75	45	235	---
7000	1499.76	45	235	---
9000	1499.77	45	235	---
12000	1499.78	45	235	---
15000	1499.78	45	235	---
18000	1499.78	45	235	---
20000	1499.78	45	235	---

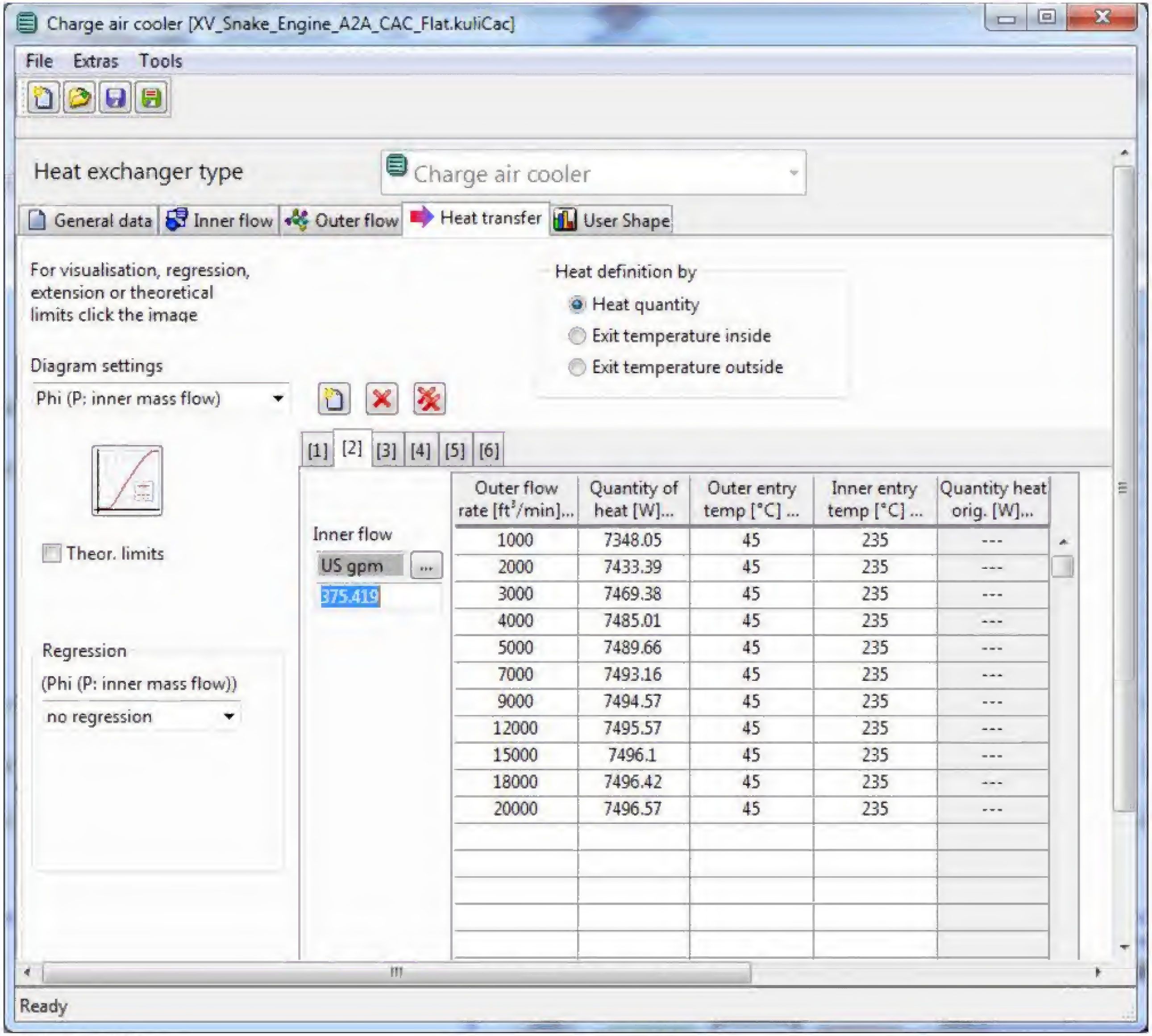
Ready

XV_Snake_Engine_A2A_CAC_Flat.kuliCac

NATIONAL ROBOTICS NREC ENGINEERING CENTER

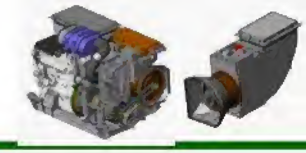
Charge Air Cooler (CAC) Parameters

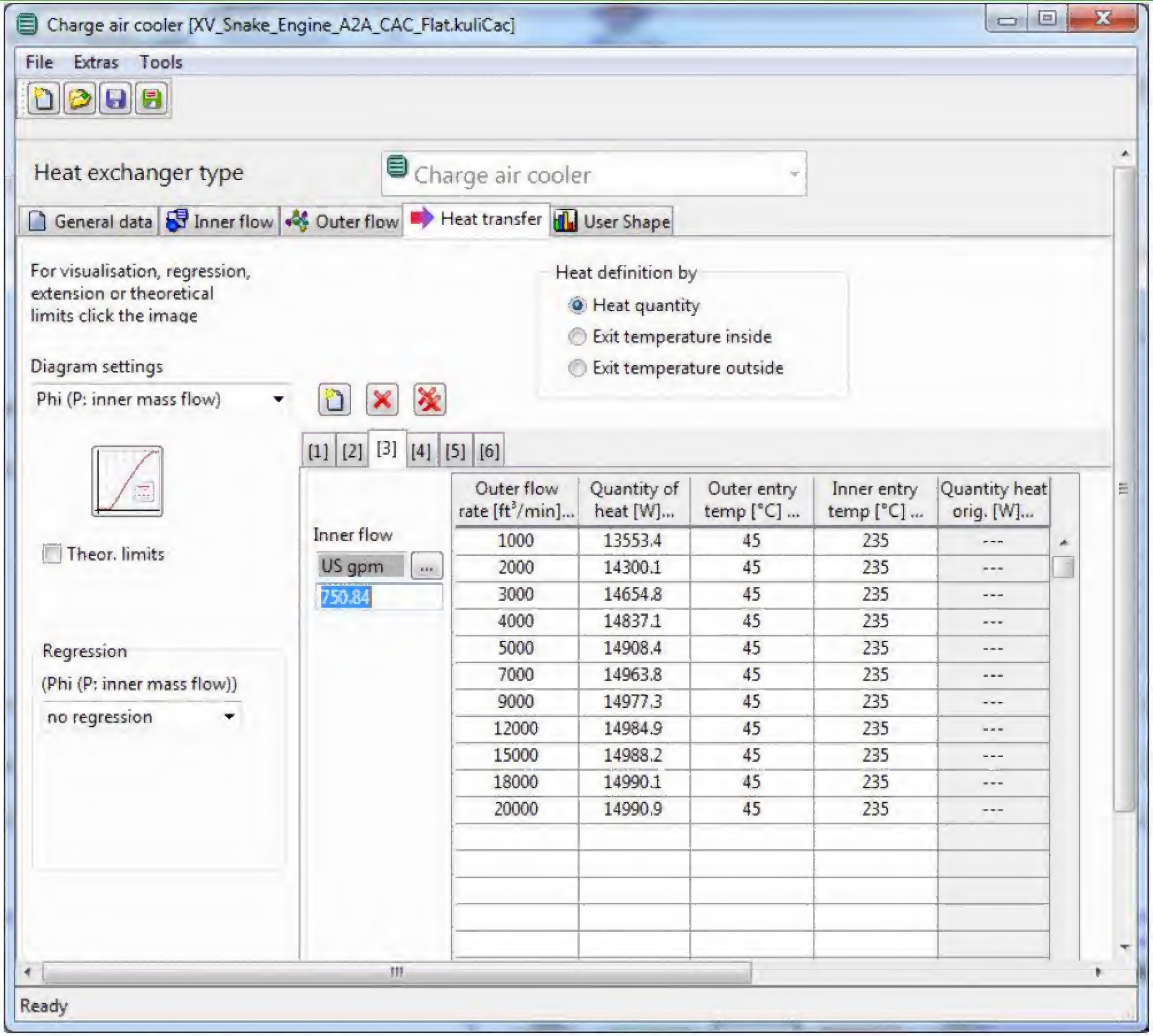




XV_Snake_Engine_A2A_CAC_Flat.kuliCac

Charge Air Cooler (CAC) Parameters

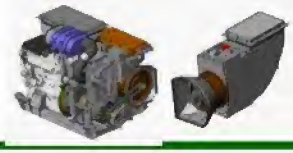


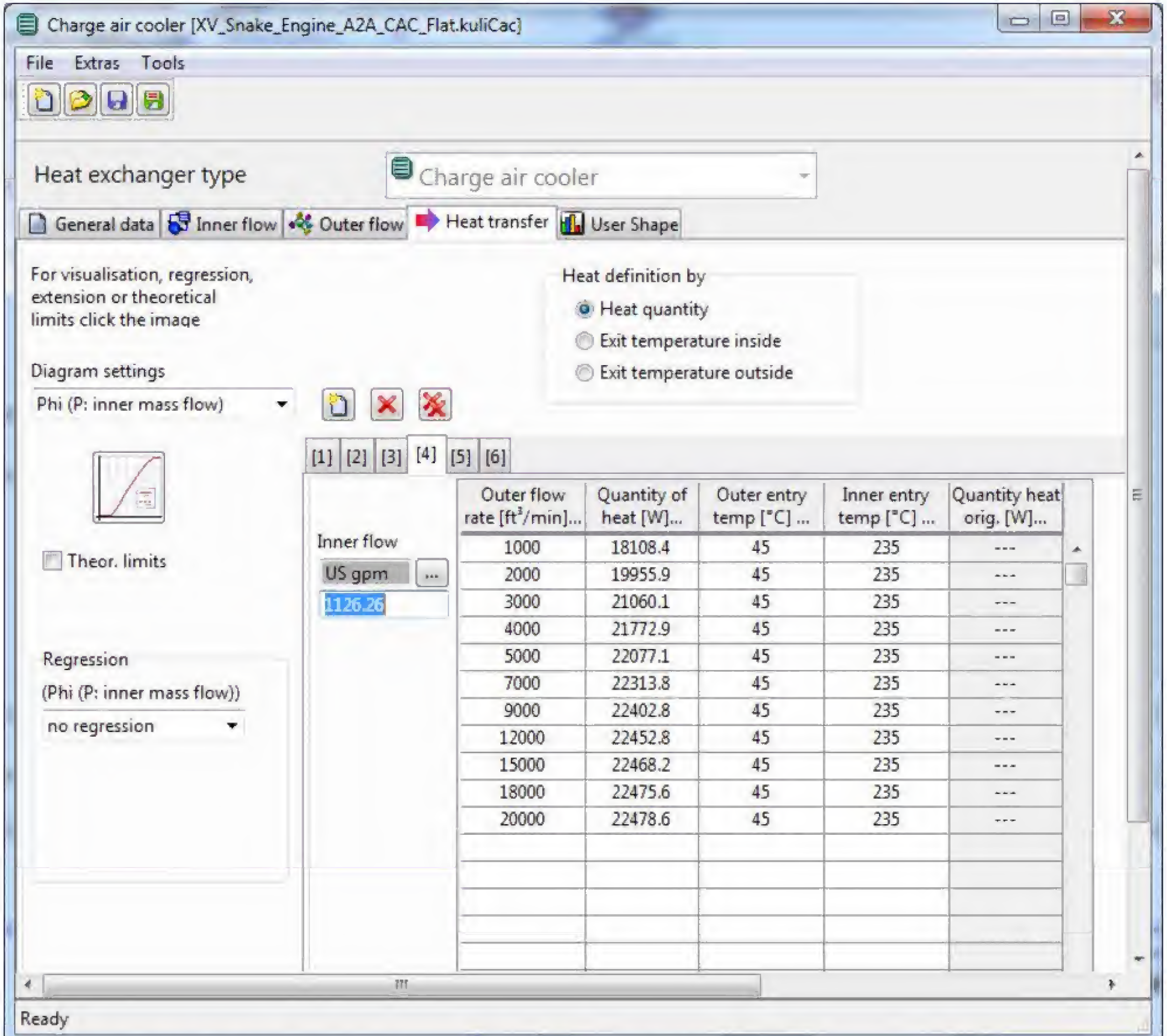


Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	13553.4	45	235	---
2000	14300.1	45	235	---
3000	14654.8	45	235	---
4000	14837.1	45	235	---
5000	14908.4	45	235	---
7000	14963.8	45	235	---
9000	14977.3	45	235	---
12000	14984.9	45	235	---
15000	14988.2	45	235	---
18000	14990.1	45	235	---
20000	14990.9	45	235	---

XV_Snake_Engine_A2A_CAC_Flat.kuliCac

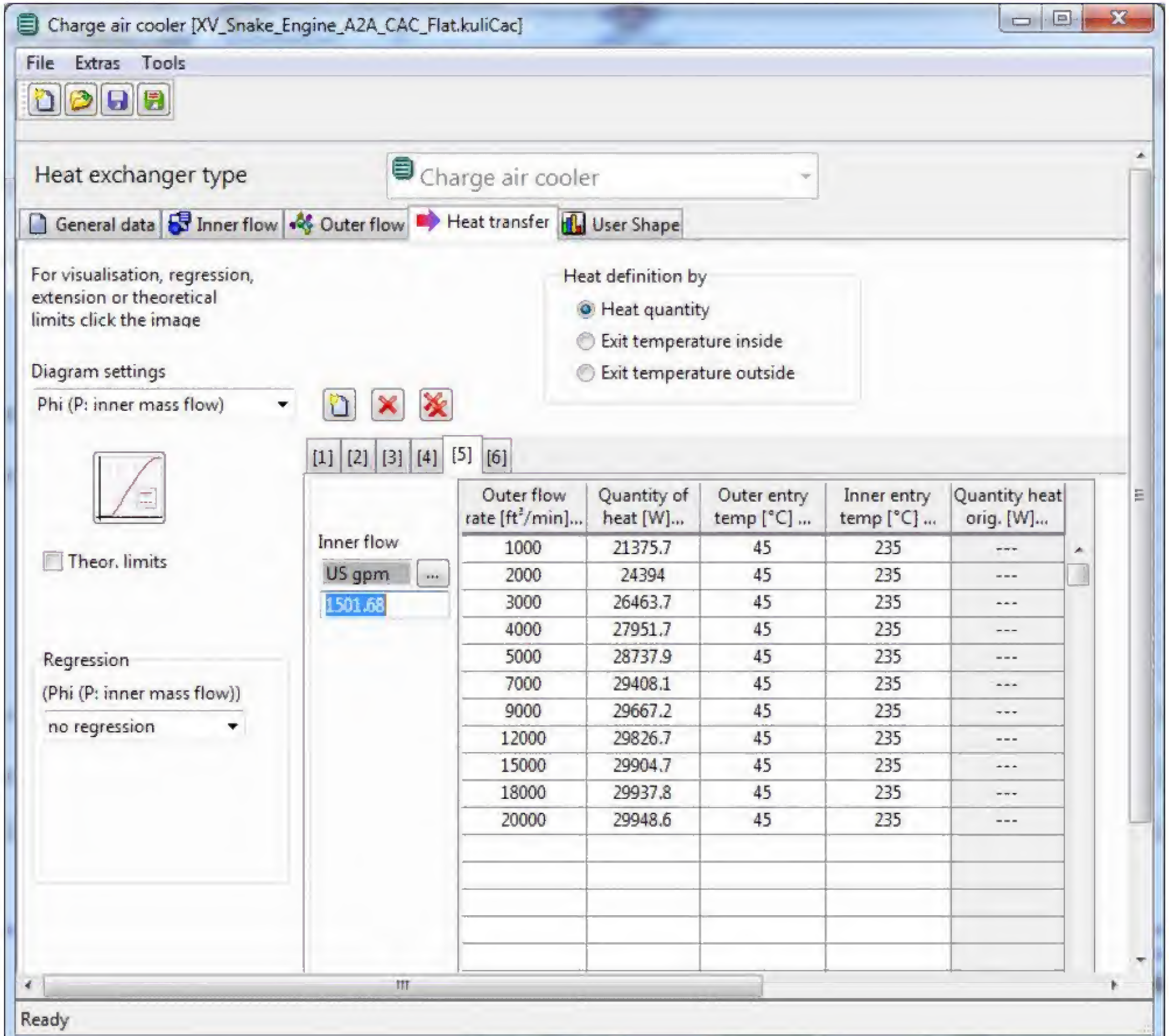
Charge Air Cooler (CAC) Parameters





XV_Snake_Engine_A2A_CAC_Flat.kuliCac

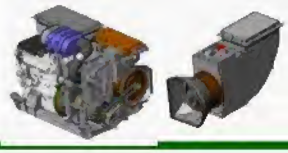
Charge Air Cooler (CAC) Parameters

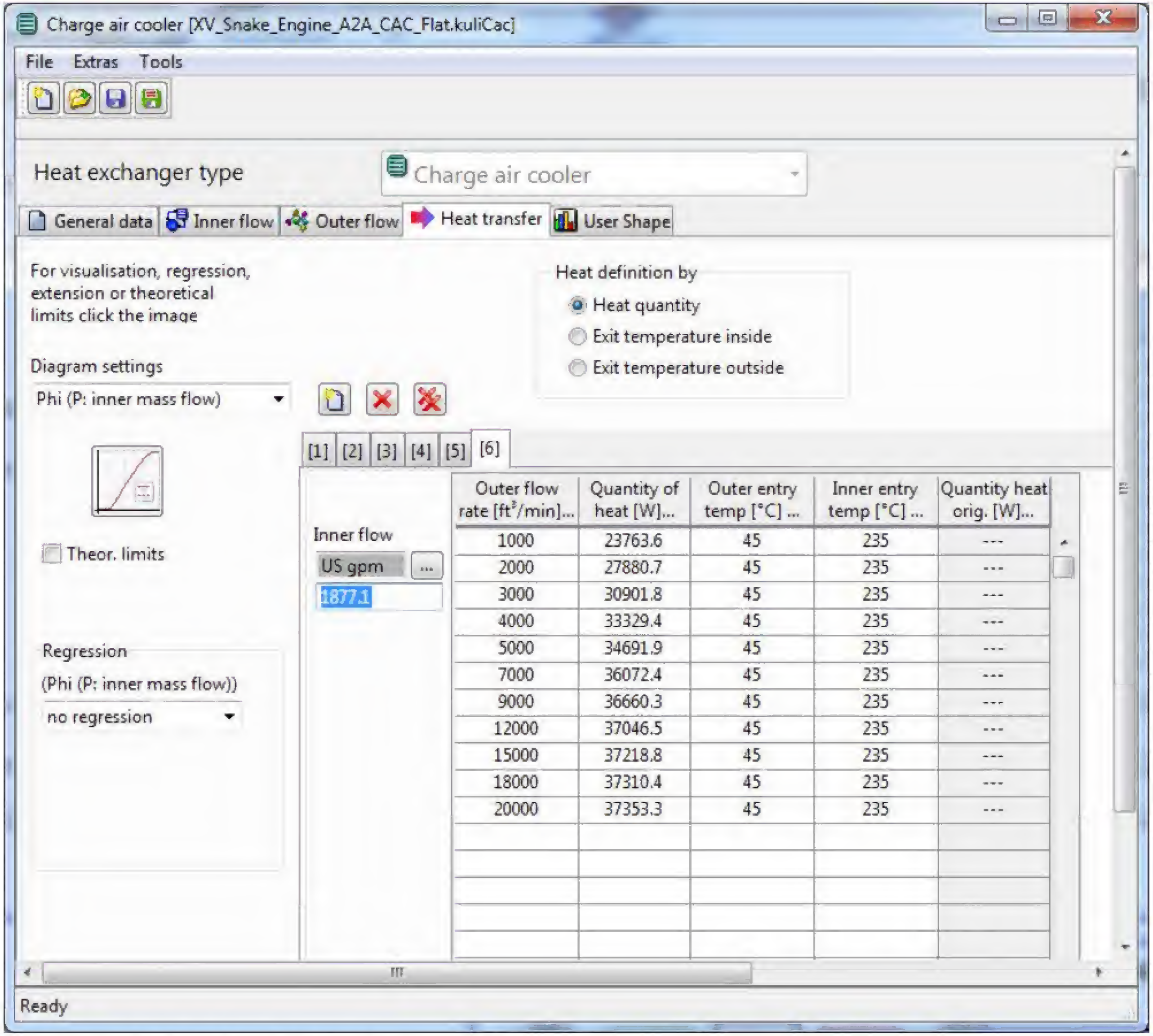


Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	21375.7	45	235	---
2000	24394	45	235	---
3000	26463.7	45	235	---
4000	27951.7	45	235	---
5000	28737.9	45	235	---
7000	29408.1	45	235	---
9000	29667.2	45	235	---
12000	29826.7	45	235	---
15000	29904.7	45	235	---
18000	29937.8	45	235	---
20000	29948.6	45	235	---

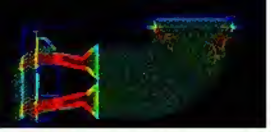
XV_Snake_Engine_A2A_CAC_Flat.kuliCac

Charge Air Cooler (CAC) Parameters

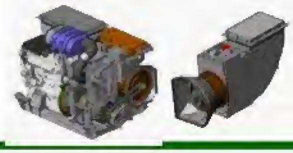


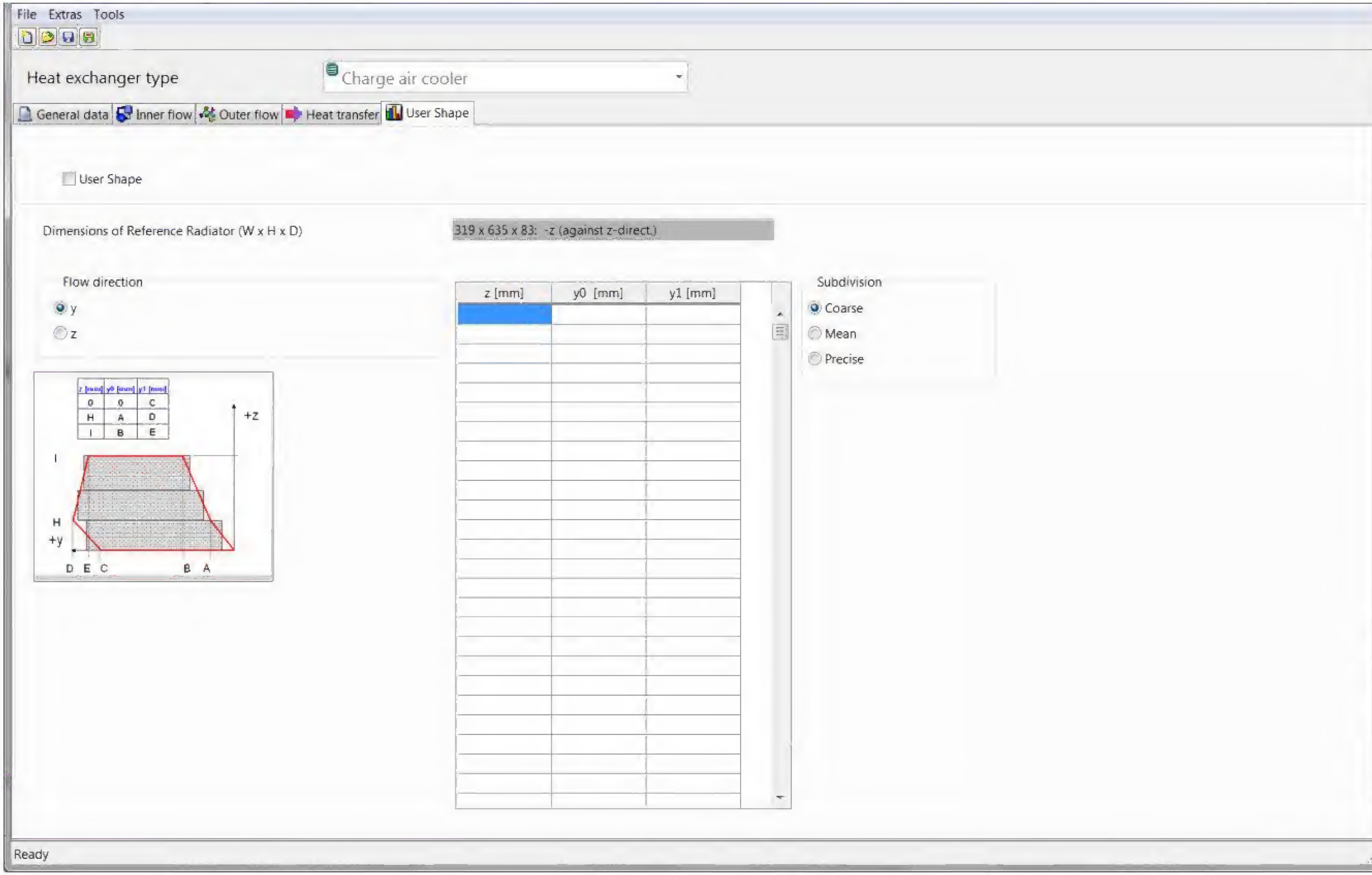


XV_Snake_Engine_A2A_CAC_Flat.kuliCac

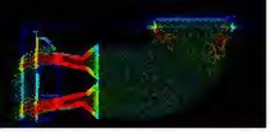


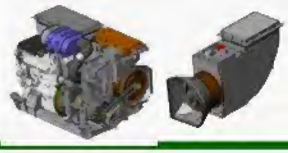
Charge Air Cooler (CAC) Parameters





XV_Snake_Engine_A2A_CAC_Flat.kuliCac



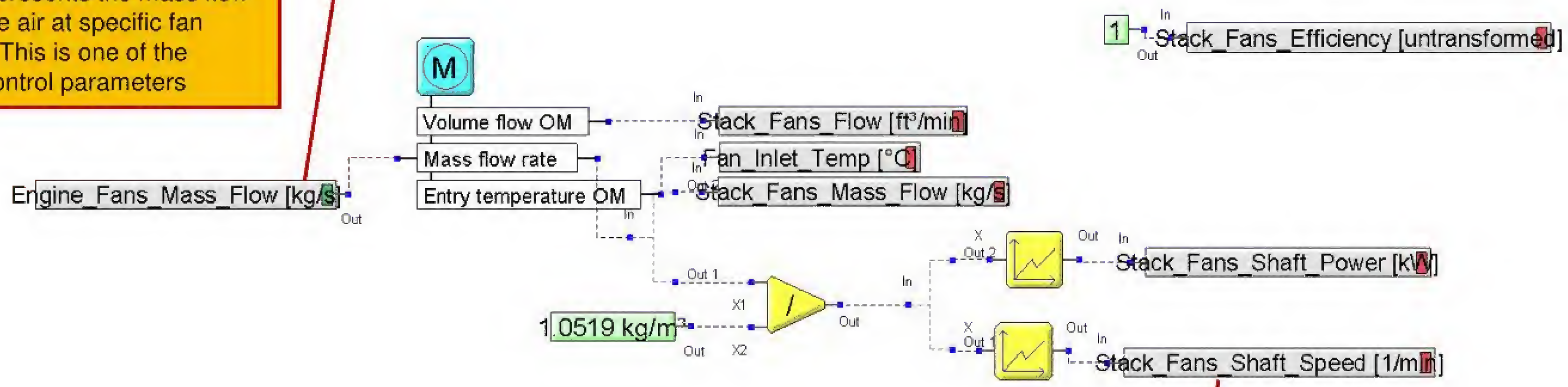


Engine Snake Air Flow

Kuli Engine Snake Air Flow

- **Input mass flow rate from Simulink**

Air flow rate through Engine Snake Heat Exchangers – The input "Engine_Fans_Mass_Flow [kg/s]" represents the mass flow rate of the air at specific fan speeds. This is one of the overall control parameters



Fan Speed and Power

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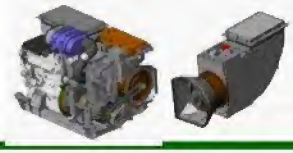
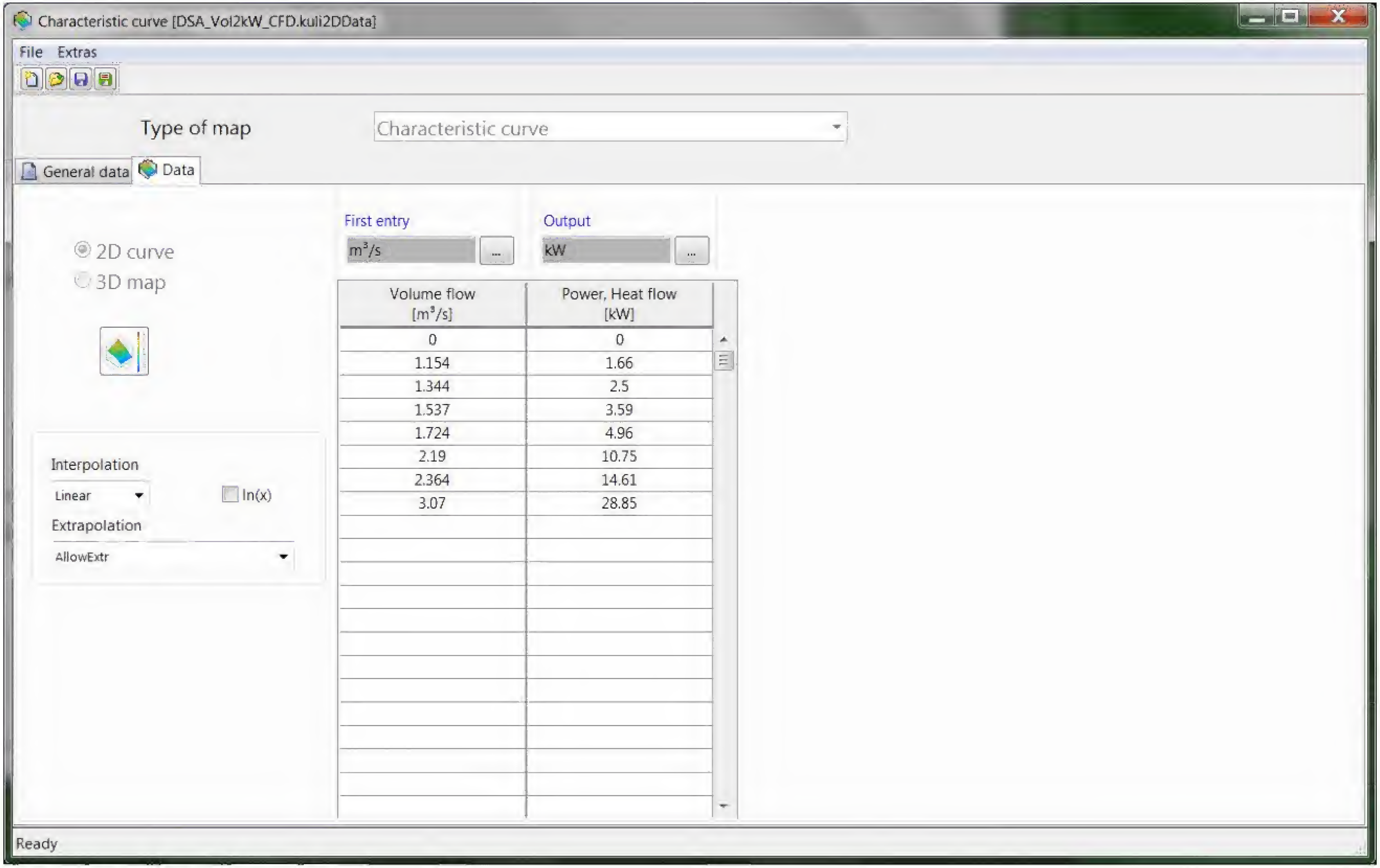
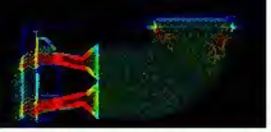
Kuli Engine Snake Air Flow - Output



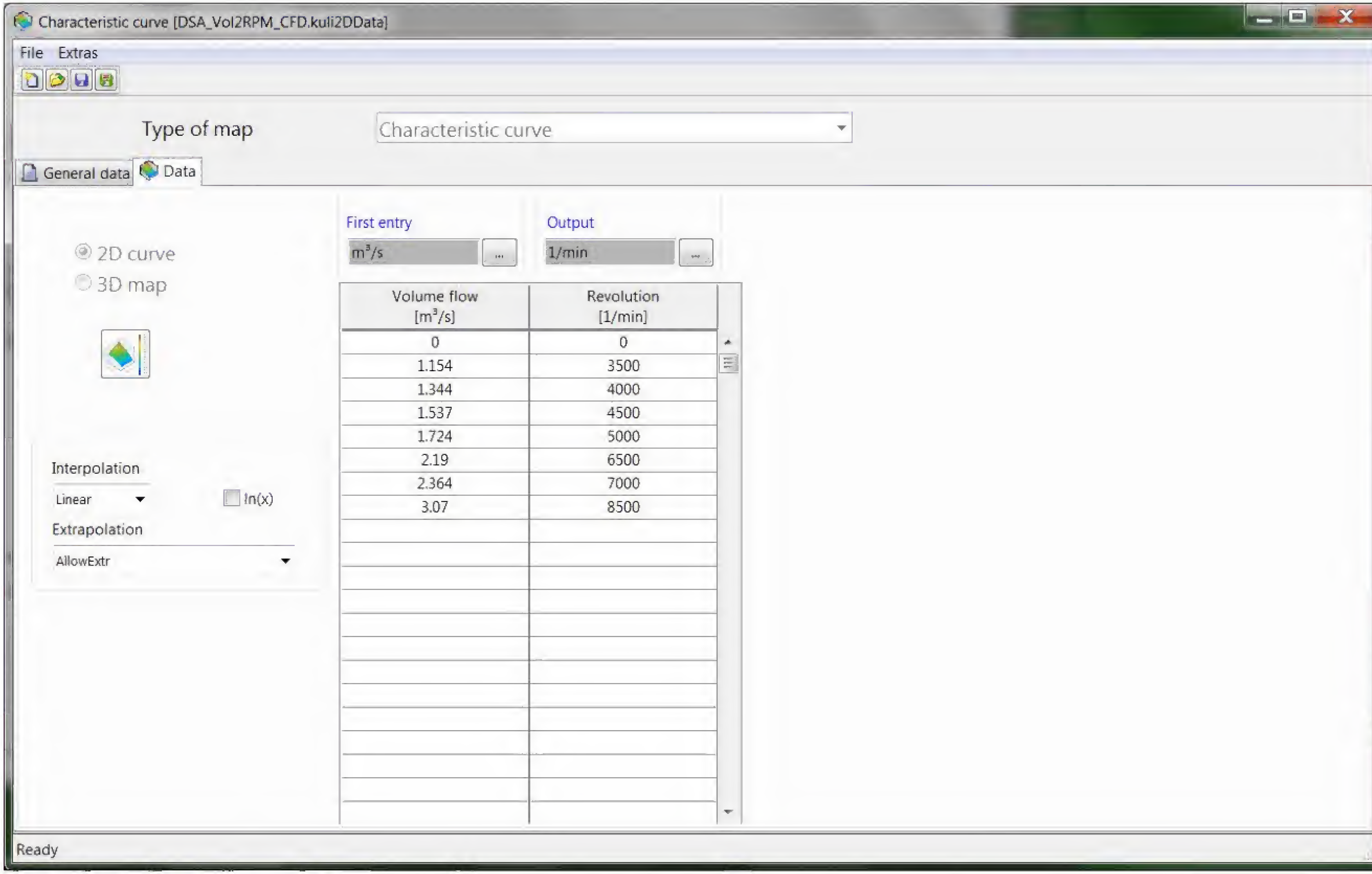


Volume flow [m³/s]	Power, Heat flow [kW]
0	0
1.154	1.66
1.344	2.5
1.537	3.59
1.724	4.96
2.19	10.75
2.364	14.61
3.07	28.85

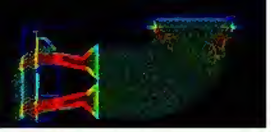
DSA_Vol2kW_CFD.kuli2DData

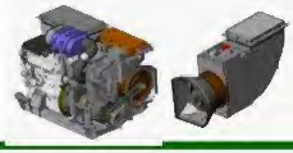


Kuli Engine Snake Air Flow - Output



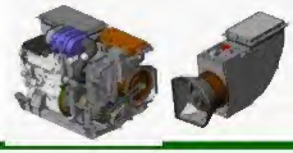
DSA_Vol2RPM_CFD.kuli2DData



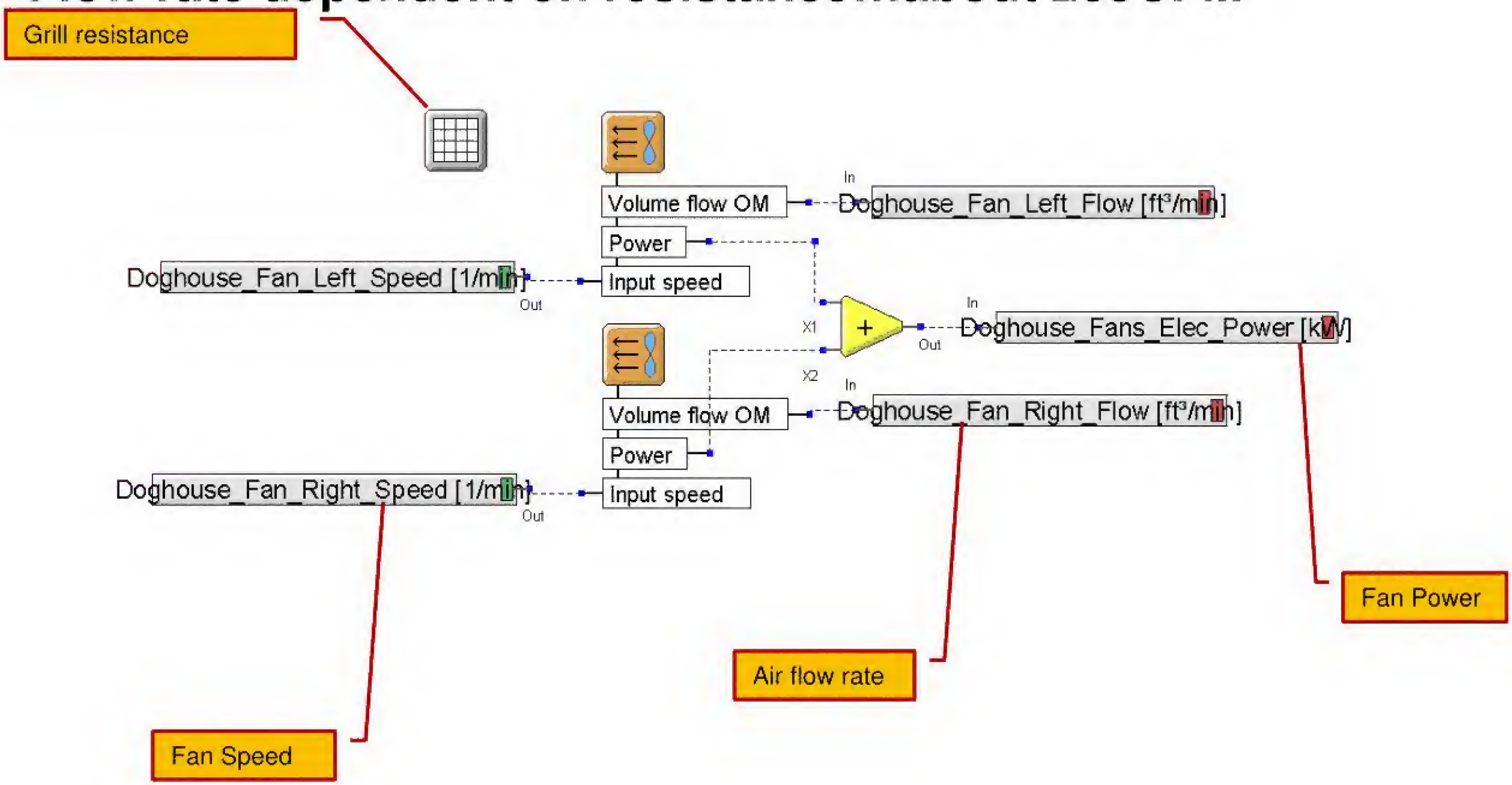


Engine Compartment Air Flow

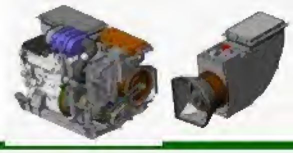
Kuli Engine Compartment Fan

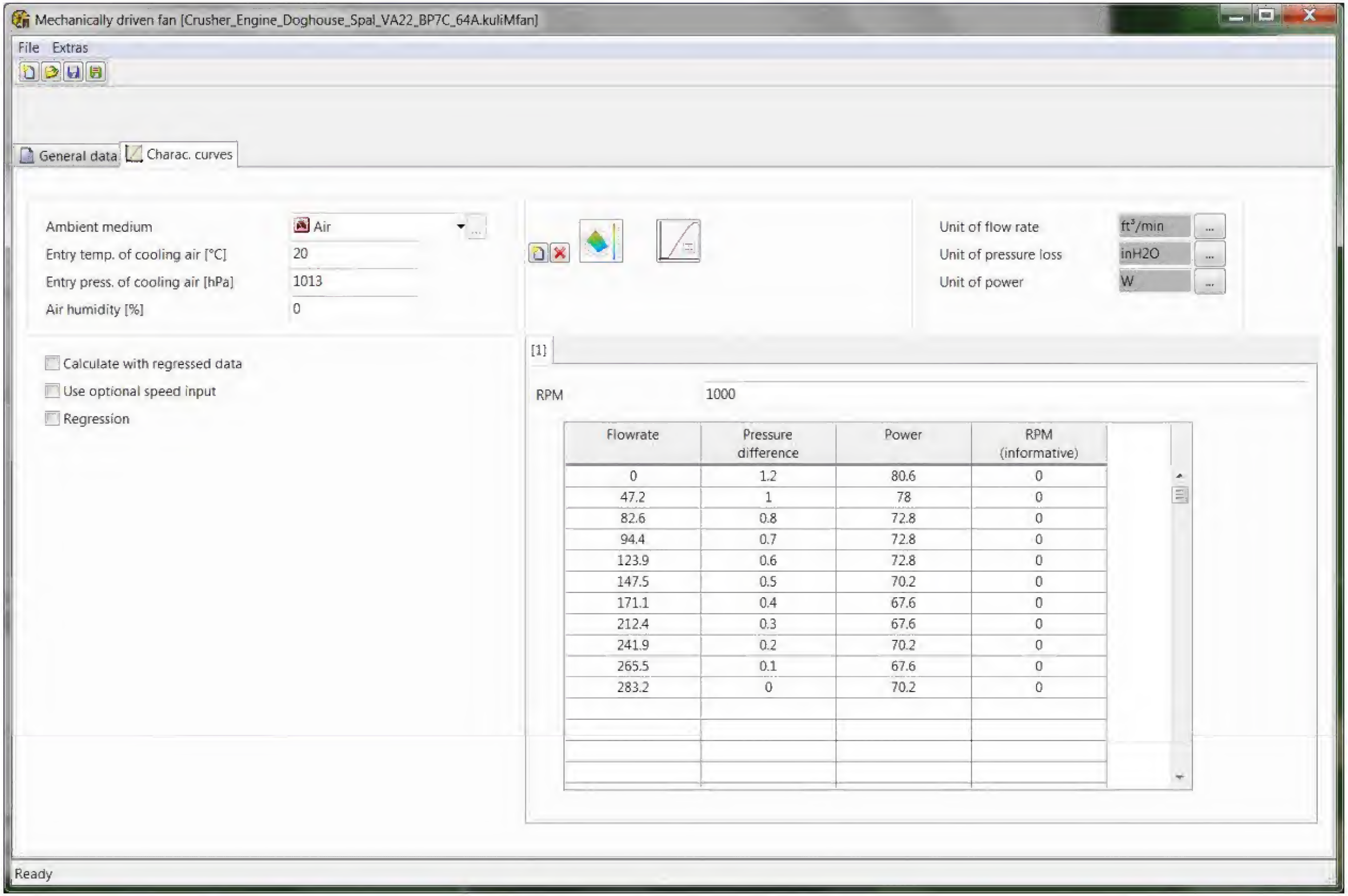


- **Pulls air through inlet grill, over engine block then out of engine compartment**
- **Flow rate dependent on resistance…about 265CFM**



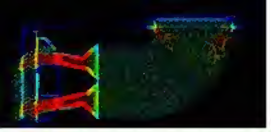
7.Mechanically Driven Fan



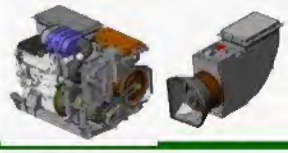


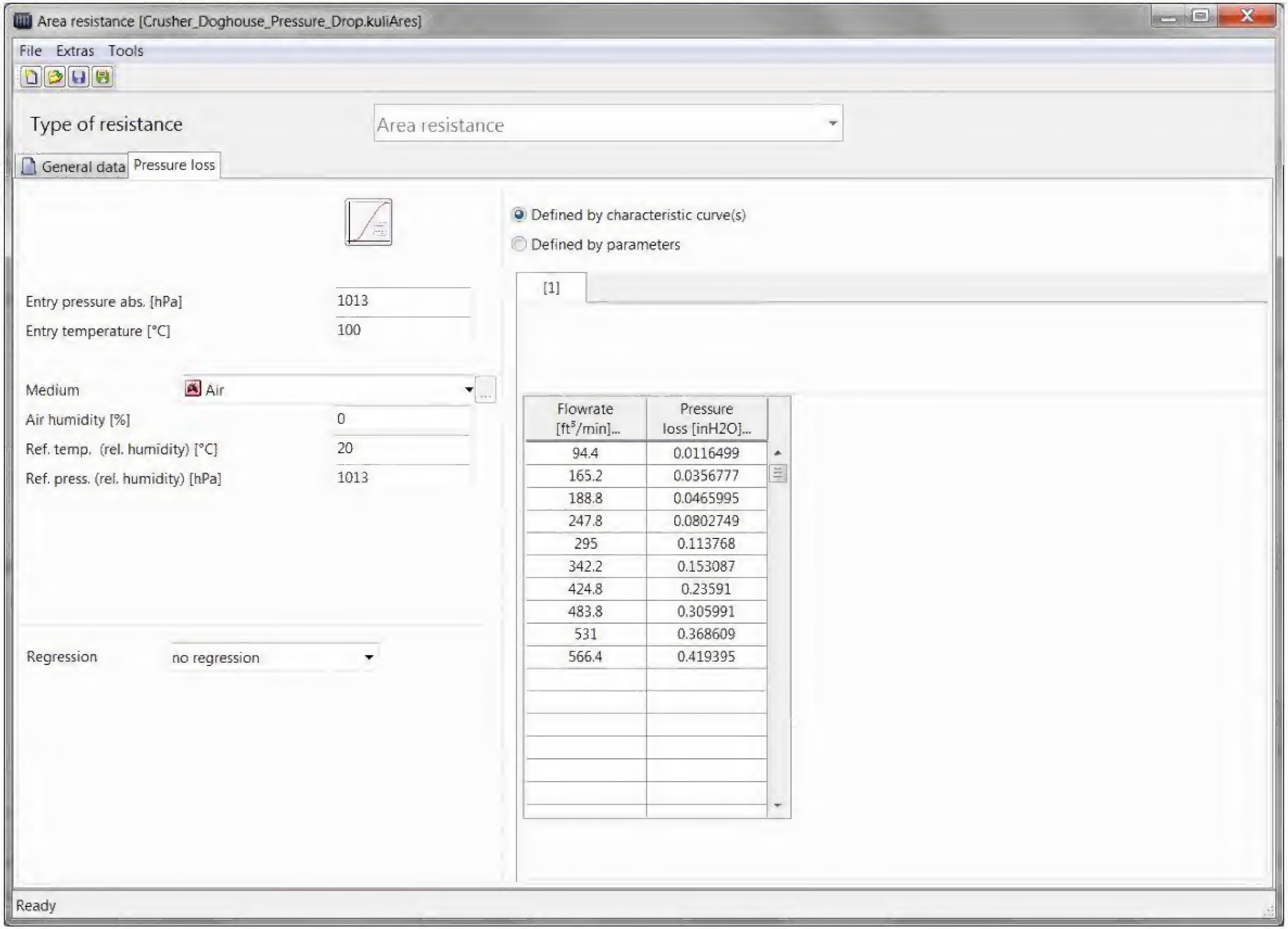
Flowrate	Pressure difference	Power	RPM (informative)
0	1.2	80.6	0
47.2	1	78	0
82.6	0.8	72.8	0
94.4	0.7	72.8	0
123.9	0.6	72.8	0
147.5	0.5	70.2	0
171.1	0.4	67.6	0
212.4	0.3	67.6	0
241.9	0.2	70.2	0
265.5	0.1	67.6	0
283.2	0	70.2	0

Crusher_Engine_Doghouse_Spal_VA22_BP7C_64A.kuliMfan

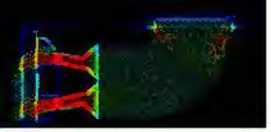


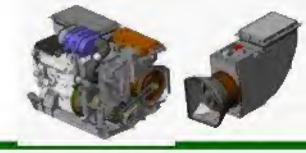
1.Area Resistance



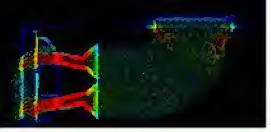


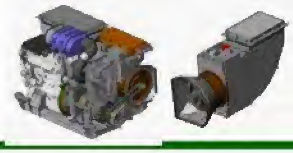
Crusher_Doghouse_Pressure_Drop.kuliAres





Drive Snake Details

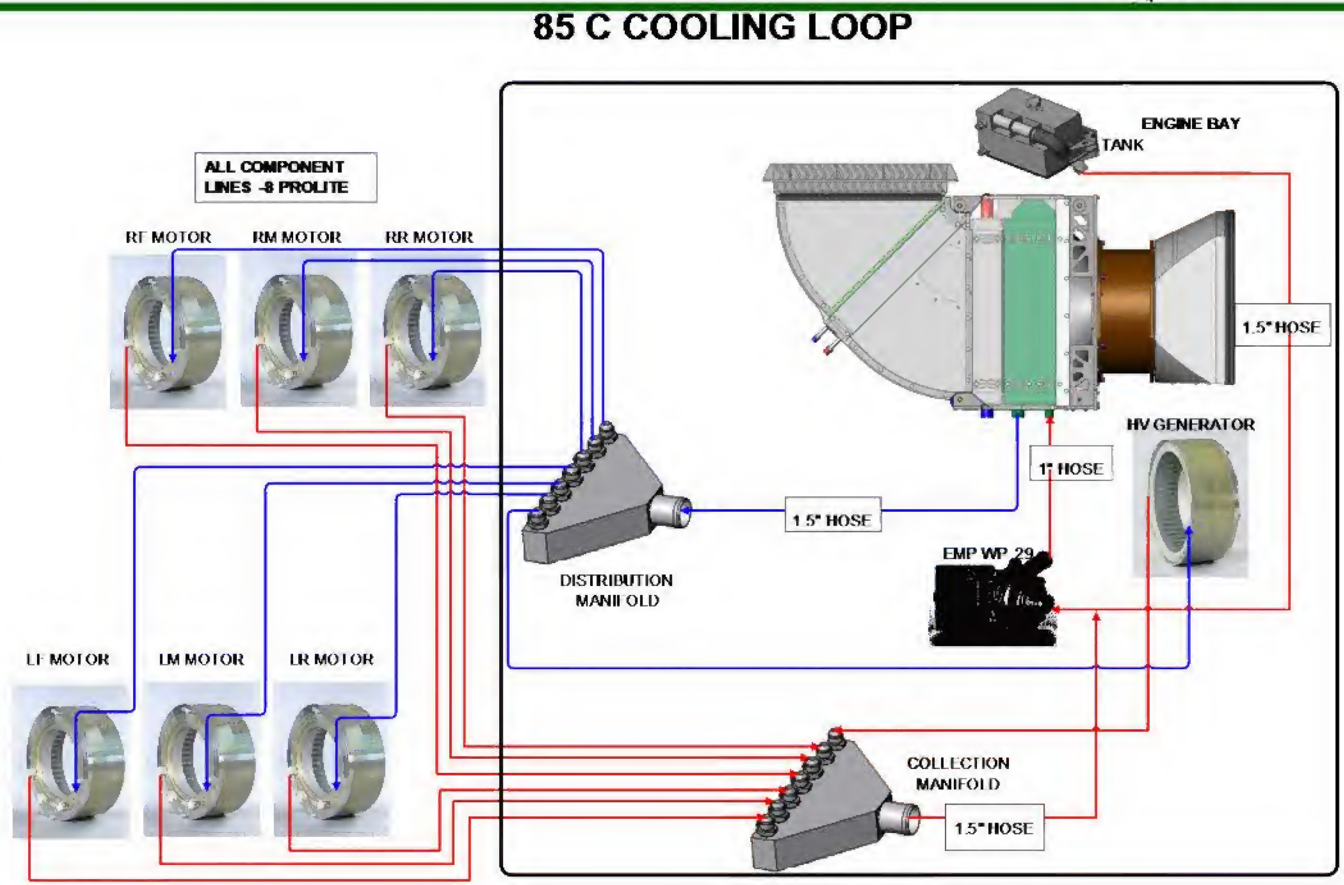


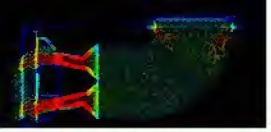


85C Loop

XV – 85C Loop

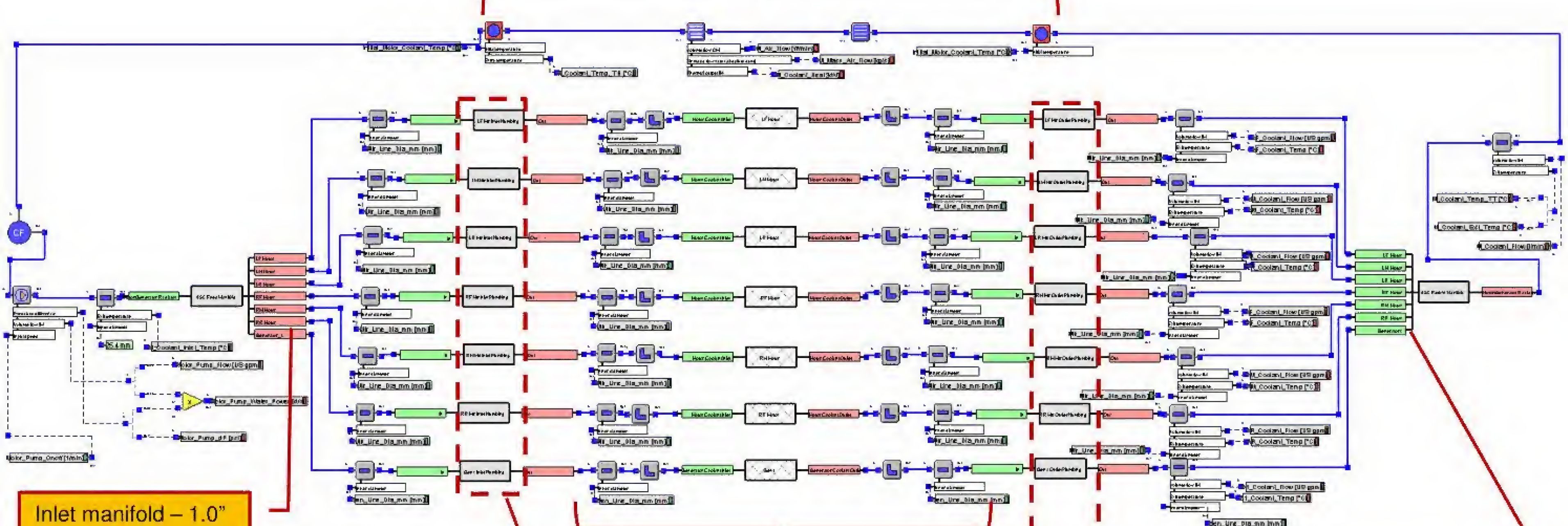
- Max load 80kph, 45C model & actual
- Flow rate – has margin, pumps not at full speed
- Loop as thermal margin, other equipment could be added
- Simplest loop





Kuli 85C Loop

Radiator (2 heat exchangers) and thermal mass



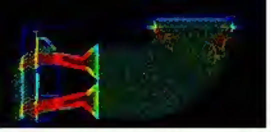
Inlet manifold – 1.0" ID inlet (from pump); 7 ea. 0.63" ID outlet

Outlet Manifolds – 7 ea 0.63" inlet; 1.5" outlet)

Feed through plumbing = neck down from 0.63" to 0.50" ID (fit through small opening in wall)

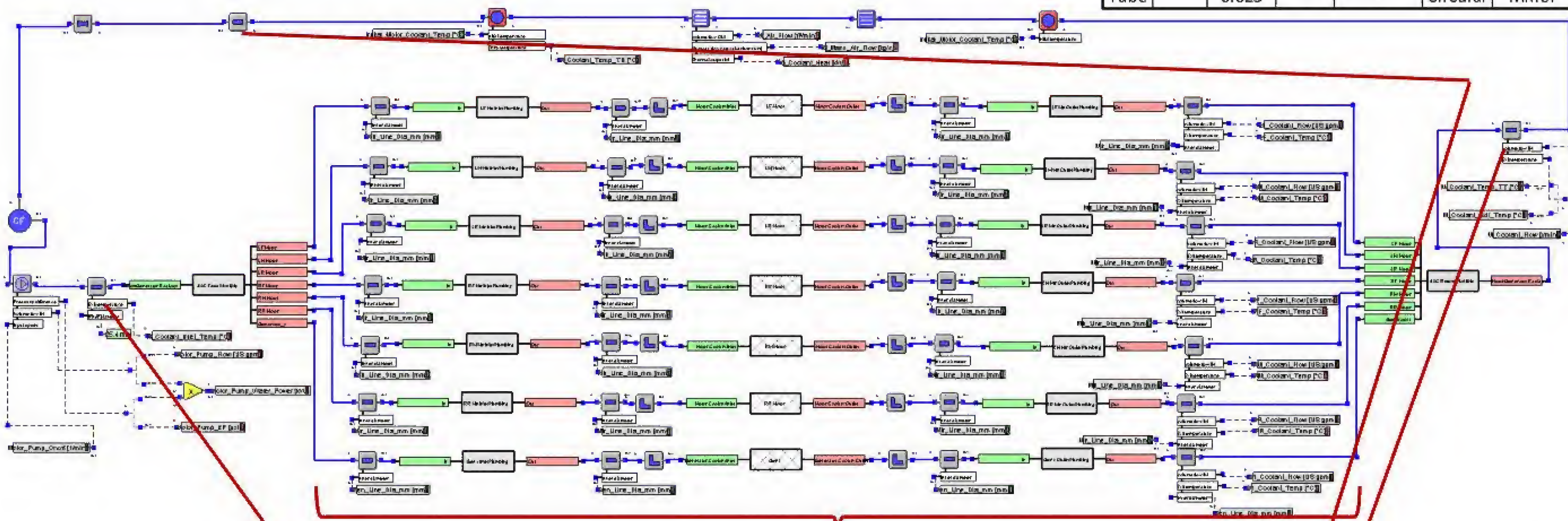
7 ea. parallel equipment coolant branches (all hoses 0.63" ID)

Equipment model = thermal mass and look up table of back pressure as a function of flow



Kuli 85C Loop Tubes and Bends

Item	ID (mm)	Pipe Rough (mm)	Angle (°)	Curvature Radius (mm)	Cross Section Shape	Pressure Drop Method	Material
Bend	16	0.0063	90	9.5	Circular	Standard	Al
Tube		0.025	-	-	Circular	Miller	Rubber Hose

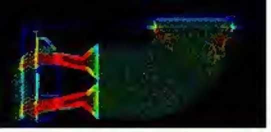


To Pumps

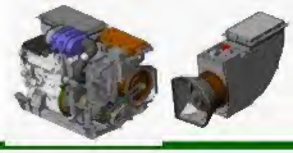
To/From Equipment

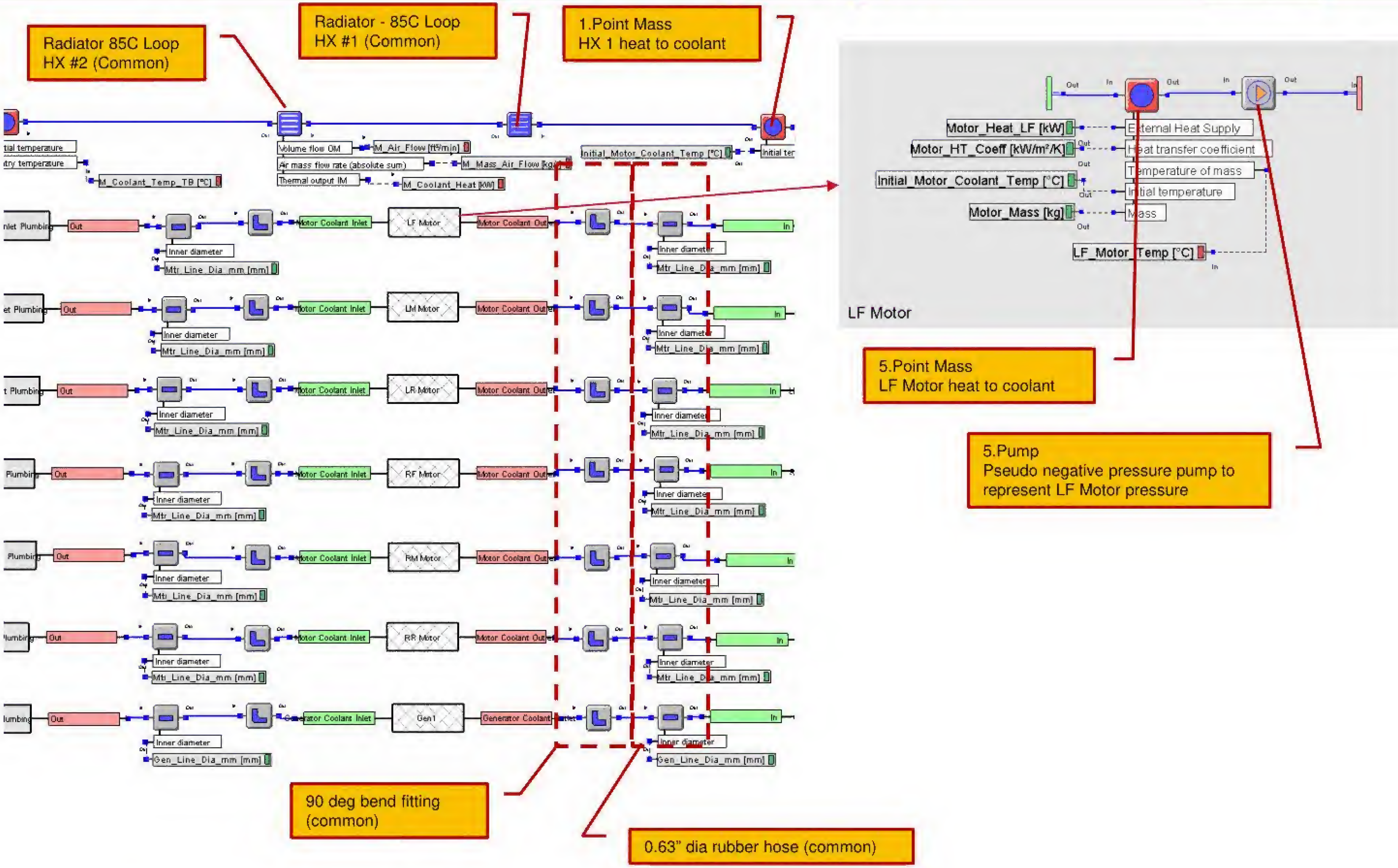
To/From Radiator

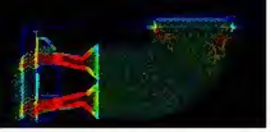
ID = 25.4 mm		ID = 16 mm								ID = 38.1 mm			
Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)
		2	2500	56	2500	63	2500	64	2500	183	750	71	750
		3	2500	50	2500	62	2500	65	2500				
		5	2500	51	2500	61	2500	66	2500				
182	500	4	2500	52	2500	60	2500	67	2500	183	750	71	750
		6	2500	53	2500	59	2500	68	2500				
		7	2500	54	2500	58	2500	69	2500				
		8	2500	55	2500	57	2500	70	2500				



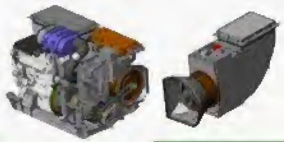
XV KULI Model – 85C Cooling Loop I/O

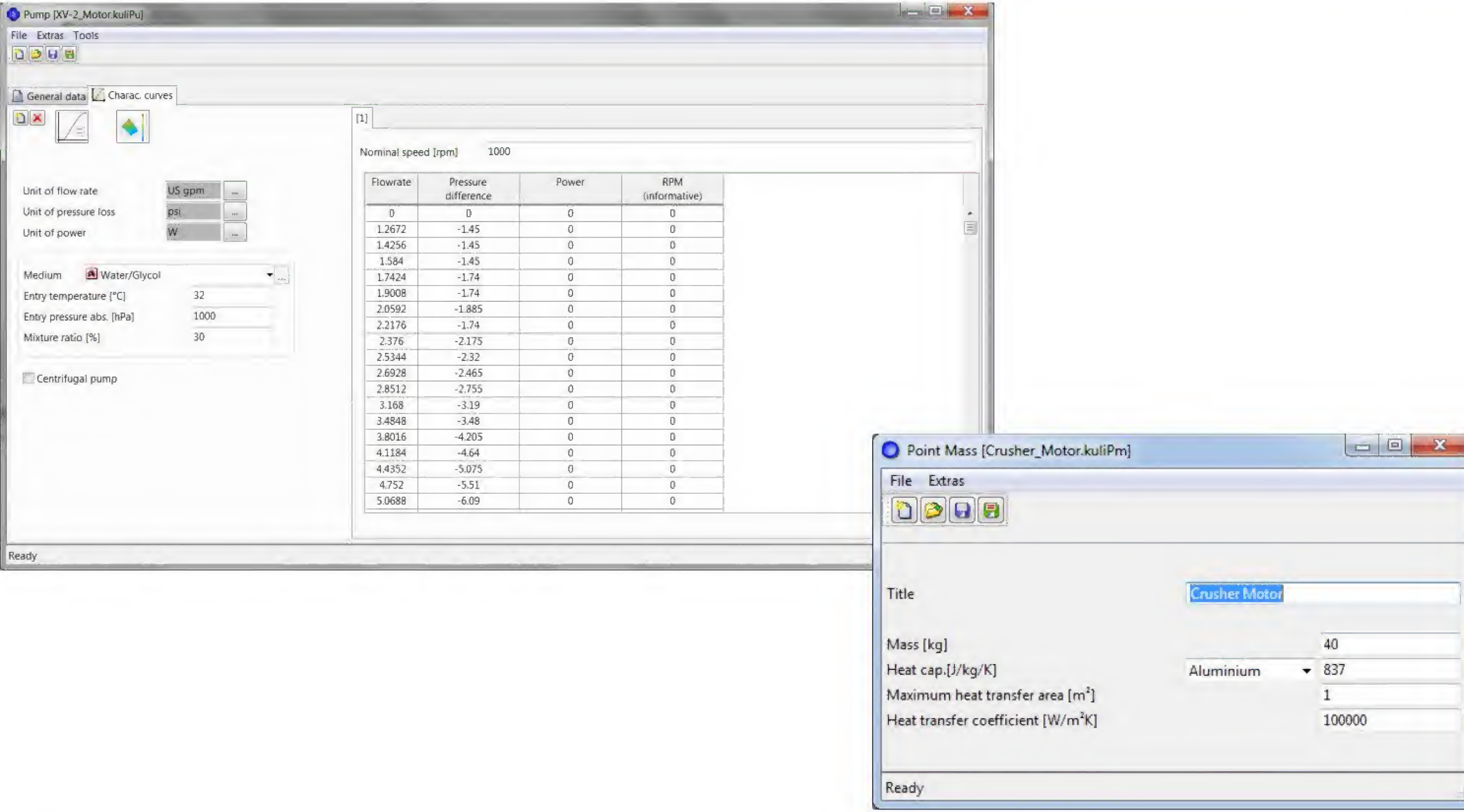






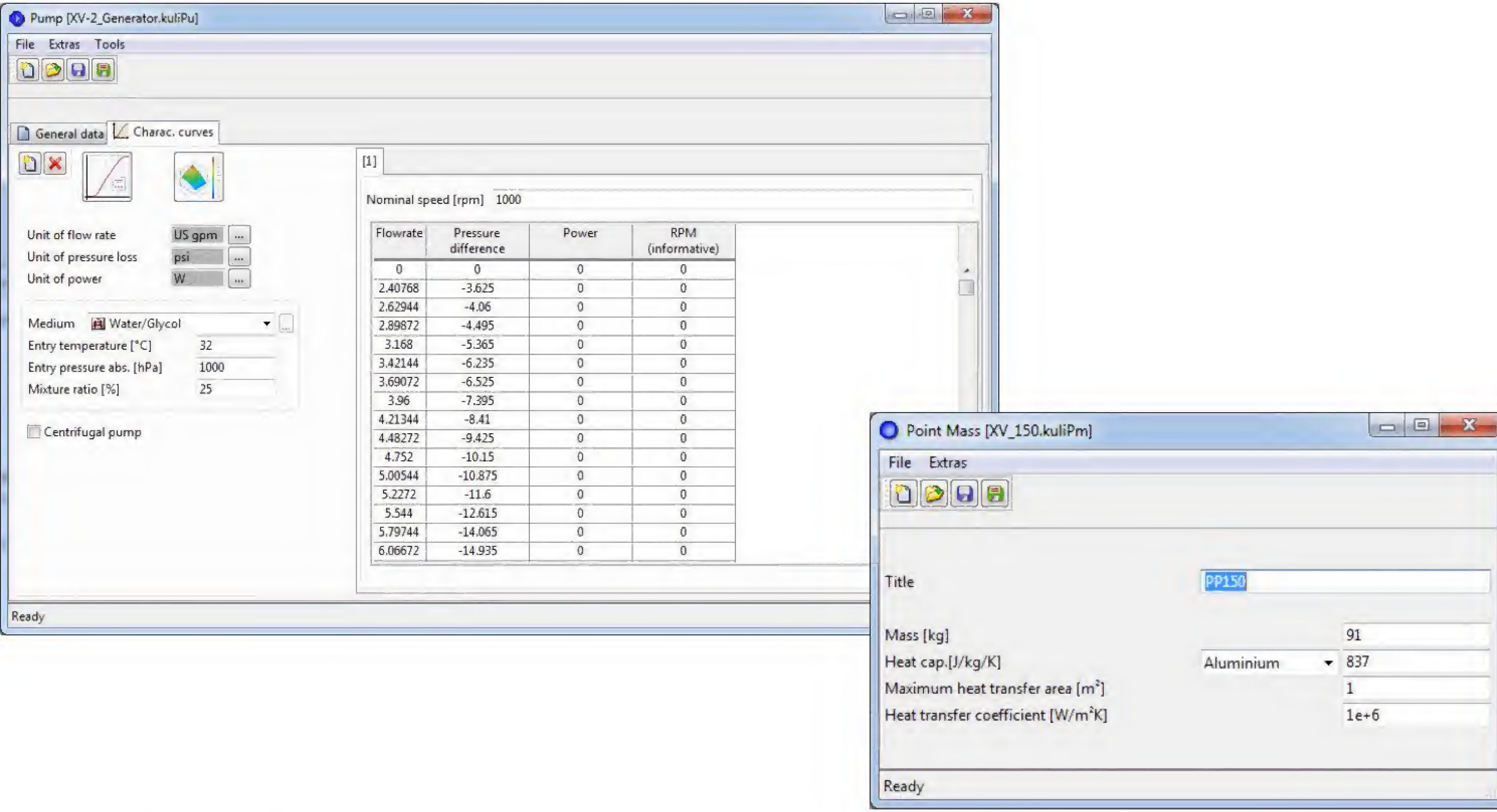
Motor Back Pressure & Point Mass (Common to all 6 motors)





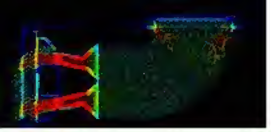
XV-2_Motor.kuliPu

Generator Back Pressure

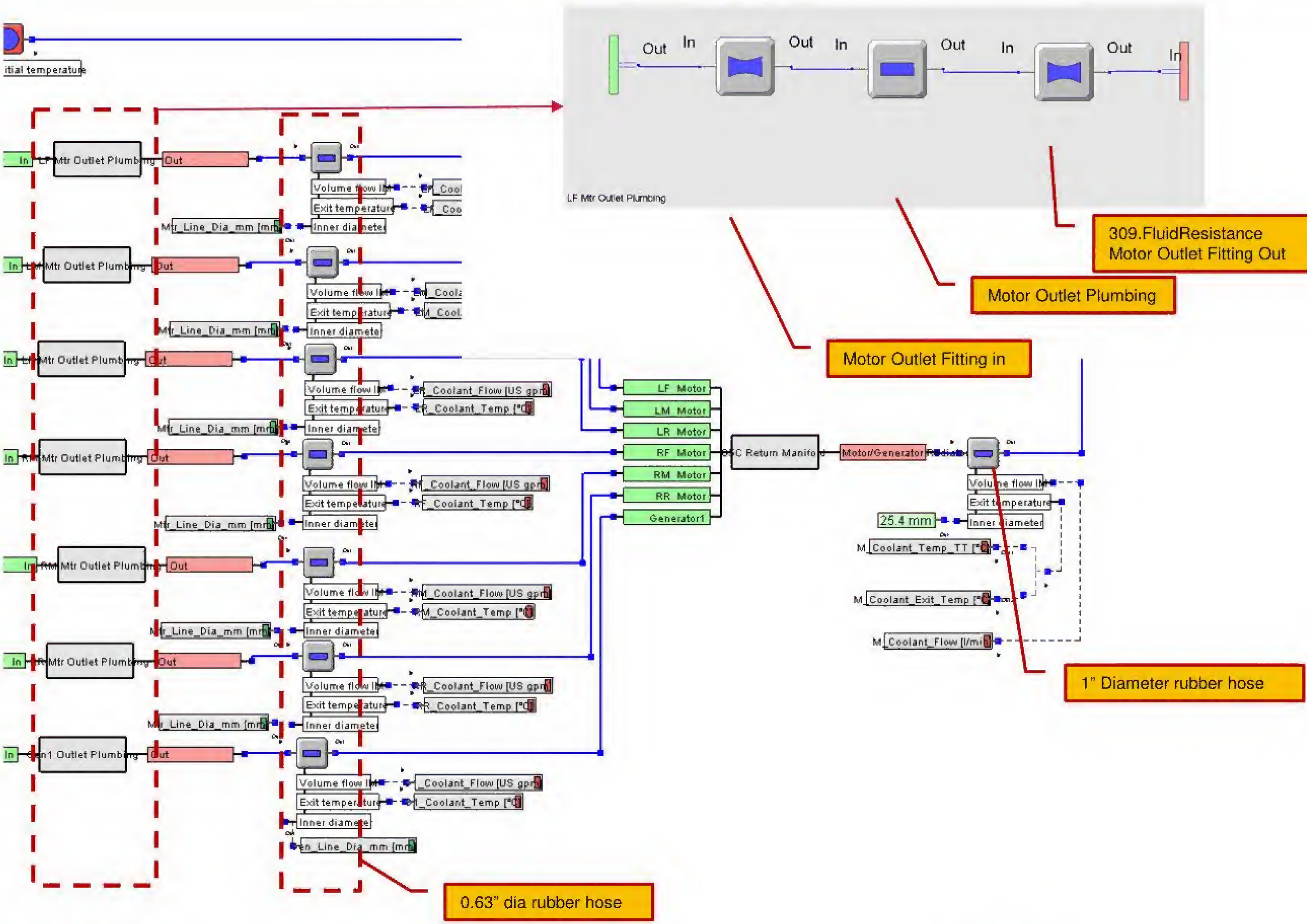


Flowrate	Pressure difference	Power	RPM (informative)
0	0	0	0
2.40768	-3.625	0	0
2.62944	-4.06	0	0
2.89872	-4.495	0	0
3.168	-5.365	0	0
3.42144	-6.235	0	0
3.69072	-6.525	0	0
3.96	-7.395	0	0
4.21344	-8.41	0	0
4.48272	-9.425	0	0
4.752	-10.15	0	0
5.00544	-10.875	0	0
5.2272	-11.6	0	0
5.544	-12.615	0	0
5.79744	-14.065	0	0
6.06672	-14.935	0	0

XV-2_Generator.kuliPu



XV KULI Model – 85C Cooling Loop I/O



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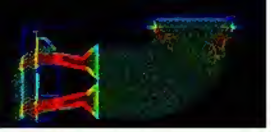
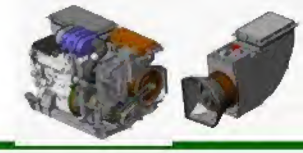
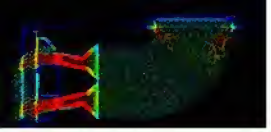


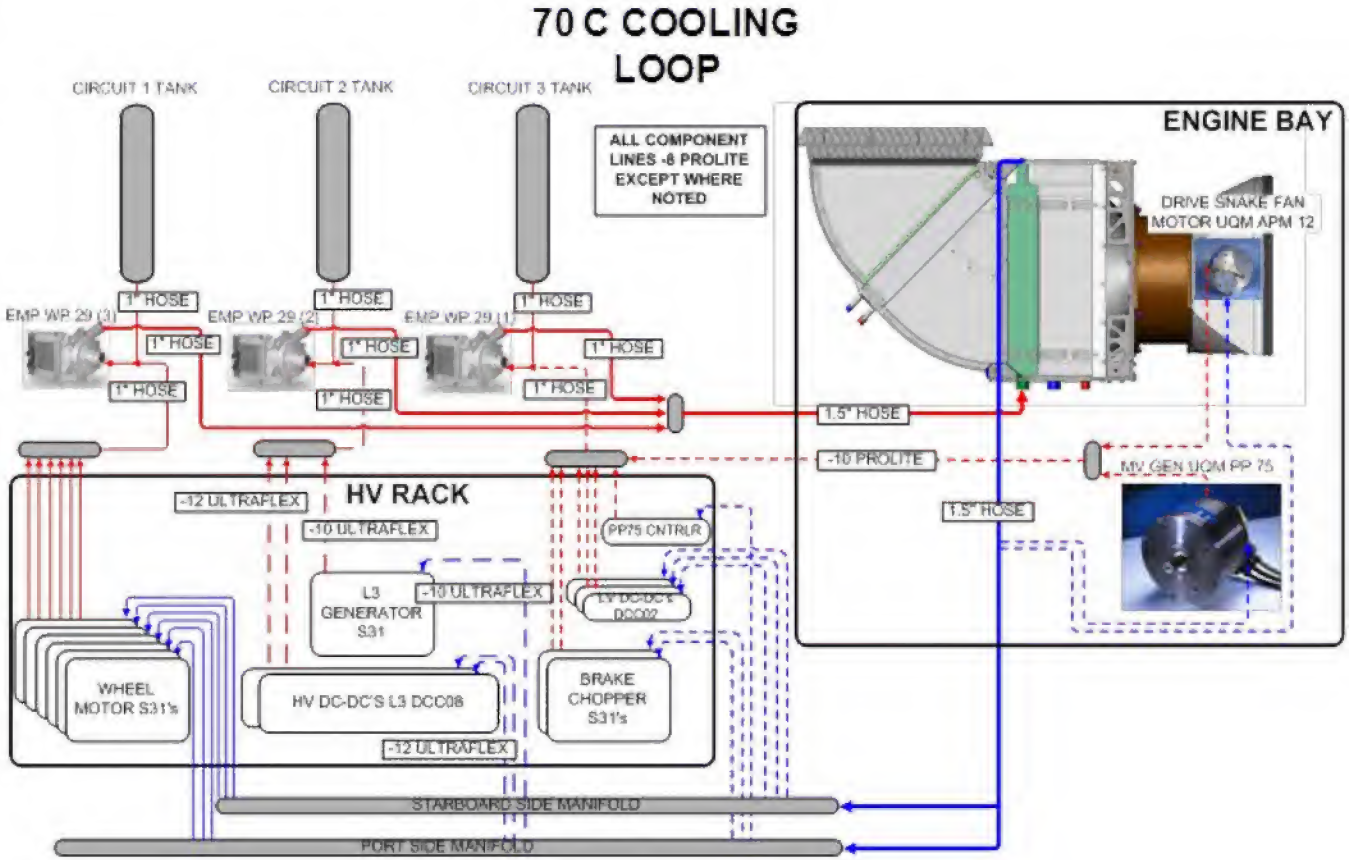


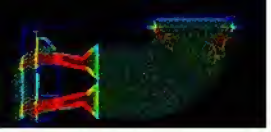
70C Loop



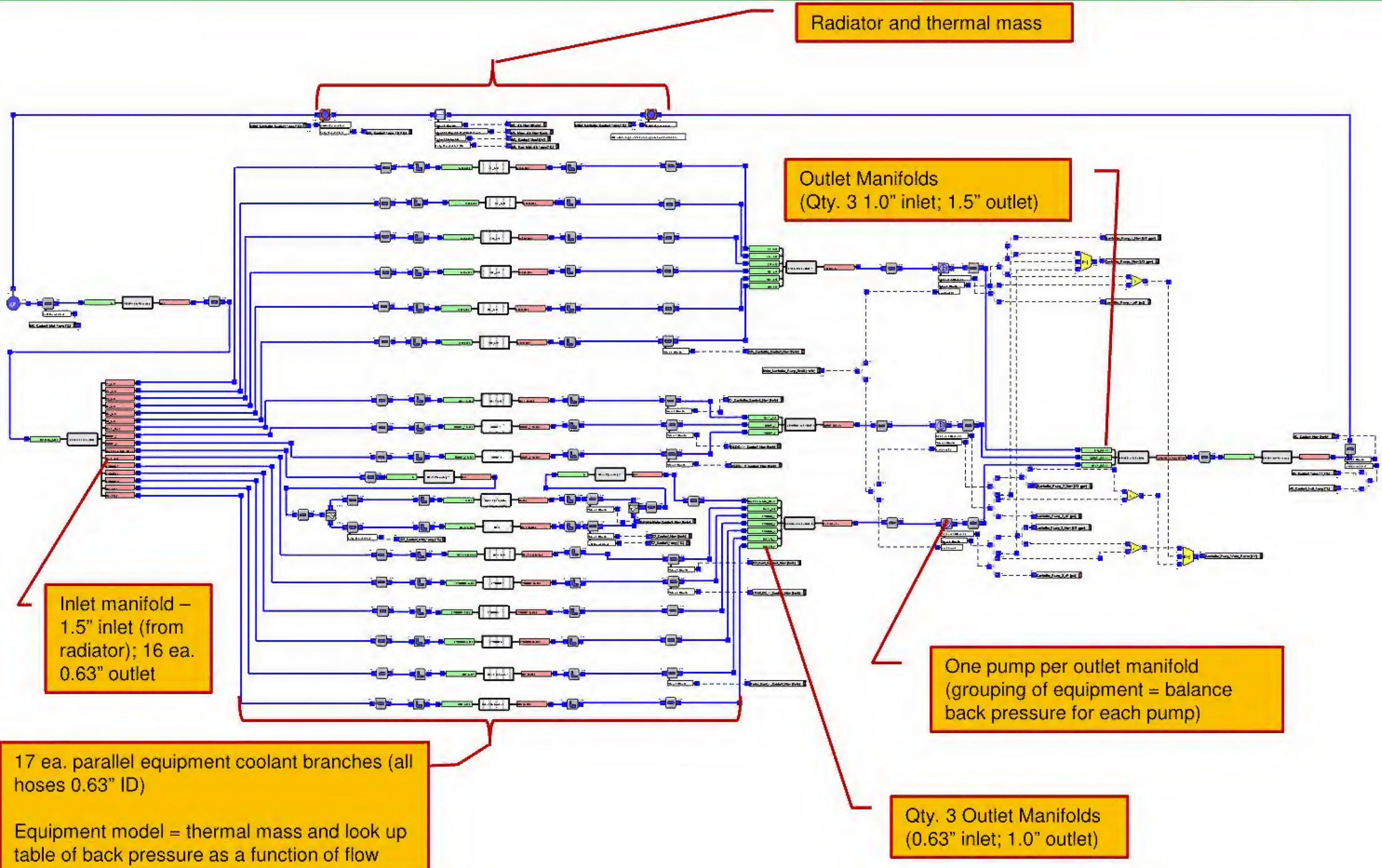
XV – 70C Loop

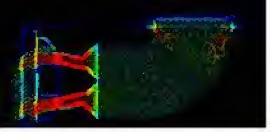
- Max load 80kph, 45C model & actual
- Flow rate – slightly less than needed after quick disconnects installed (losses)
- Loop at limit (model & actual)
- 70C loop limited performance
- Slightly higher coolant flow rate – XV would have run at 45C, full solar



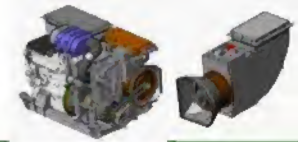


Kuli 70C Loop

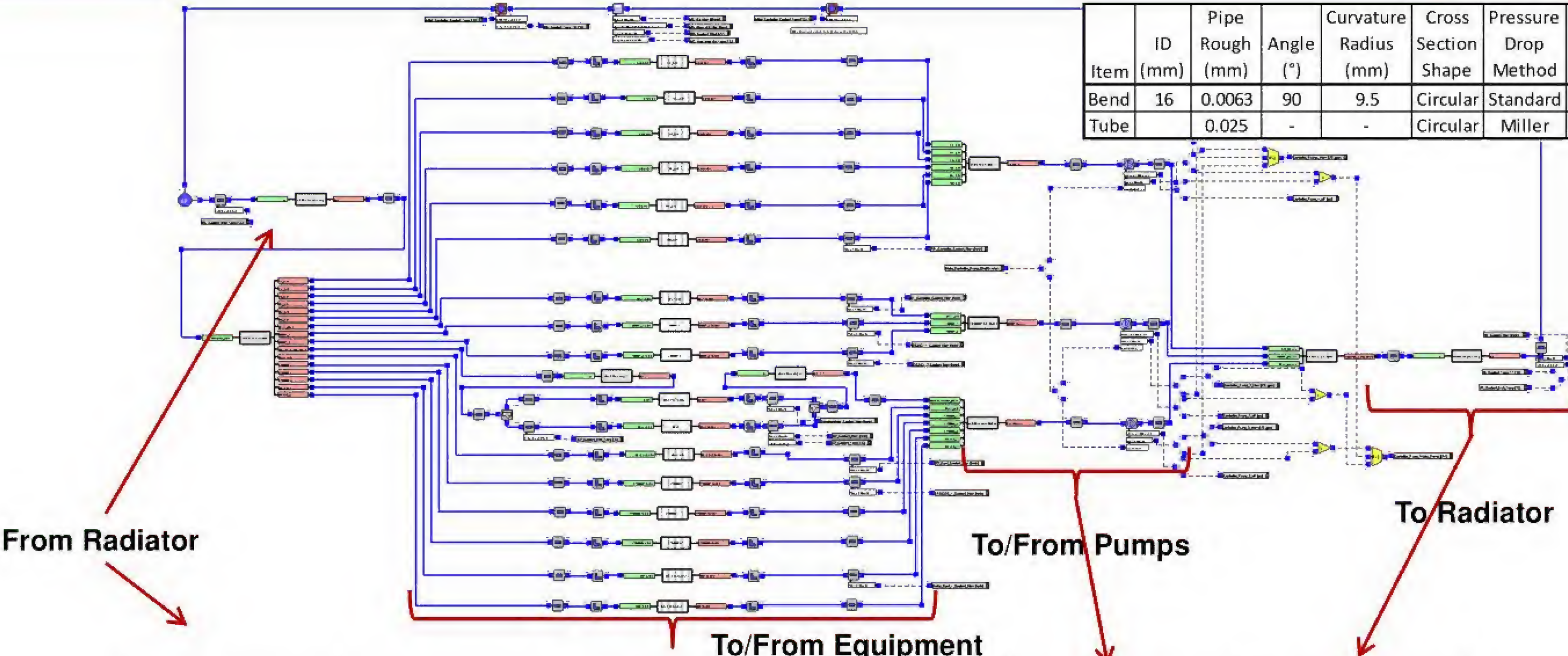




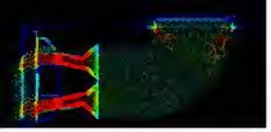
Kuli 70C Loop Tubes and Bends



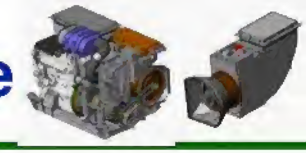
Item	ID (mm)	Pipe Rough (mm)	Angle (°)	Curvature Radius (mm)	Cross Section Shape	Pressure Drop Method	Material
Bend	16	0.0063	90	9.5	Circular	Standard	Al
Tube		0.025	-	-	Circular	Miller	Rubber Hose

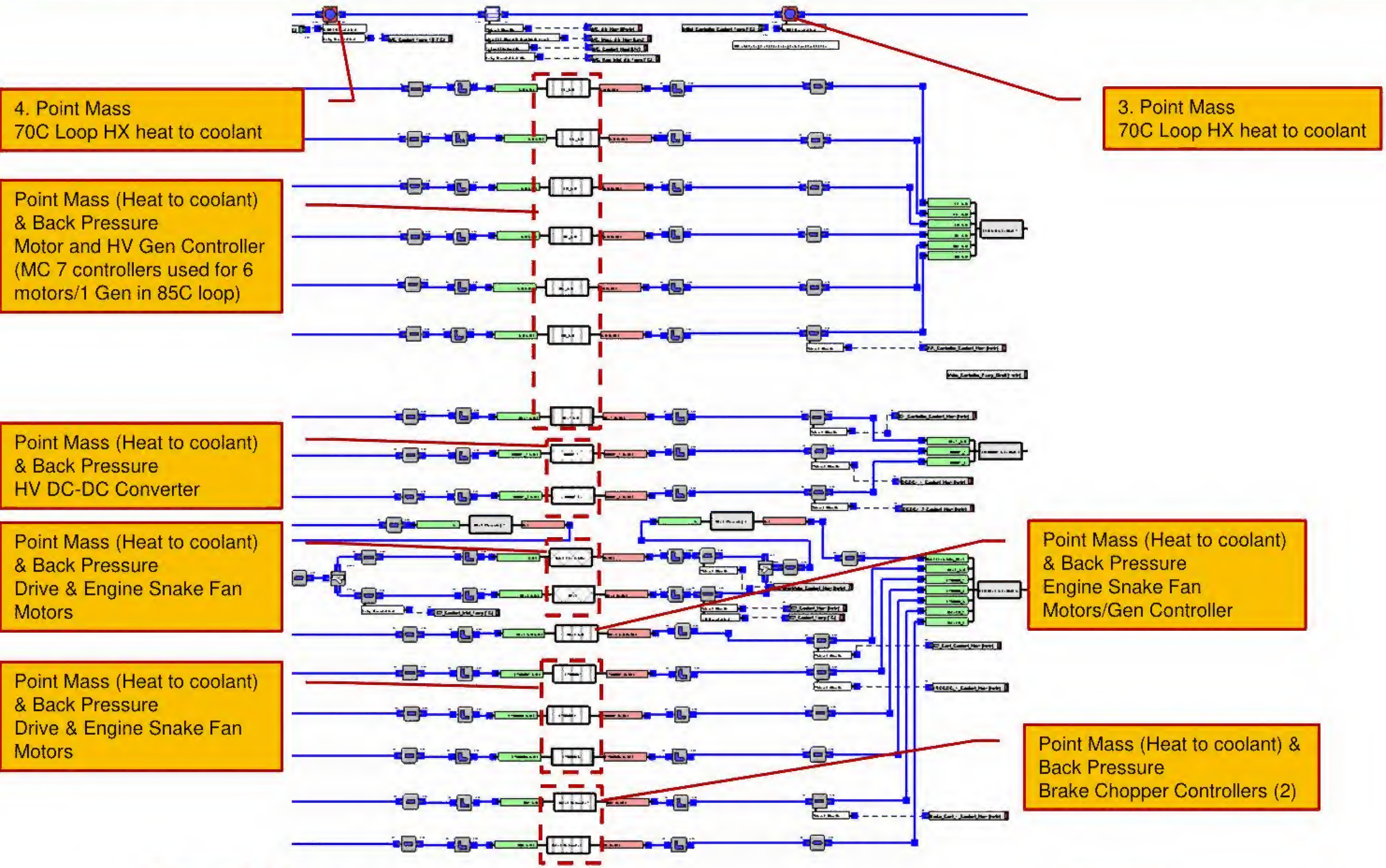


ID = 38.1 mm				ID = 16 mm												ID = 25.4 mm				ID = 38.1 mm			
Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)
				72	500									98	500	183	750	71	750				
				73	500									91	500								
				76	500									87	500								
				75	500									89	500								
				77	500									85	500								
				78	500									84	500								
				79	500									81	500	184	750	144	750	191	500	74	3250
				131	500									134	500								
182	500	190	3250	138	500									136	500								
				181	2500	187	250	178	500	175	500	186	250	188	2500	185	750	143	750				
				123	500			122	500	119	500			126	500								
				146	500									147	500								
				151	500									152	500								
				155	500									156	500								
				162	500									163	500								
				160	500									159	500								



Kuli 70C Loop Point Mass & Back Pressure





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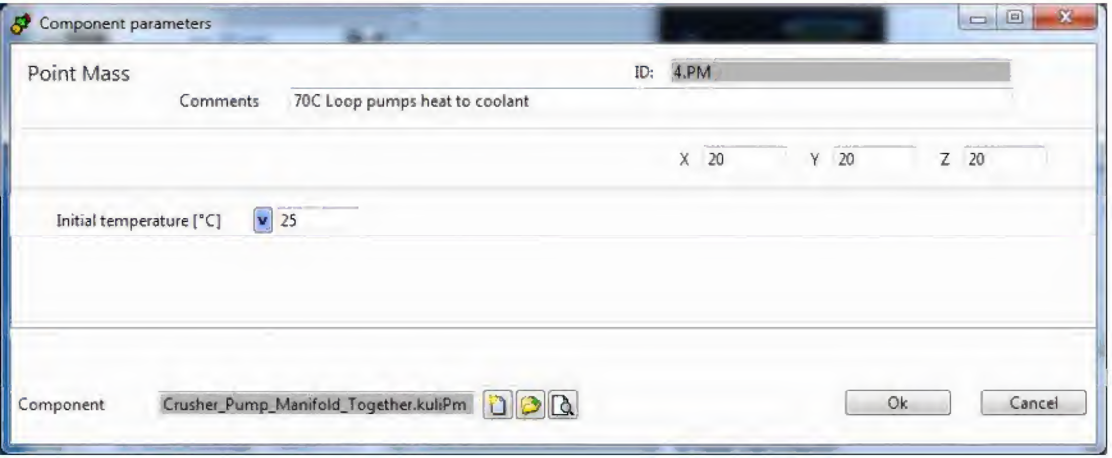
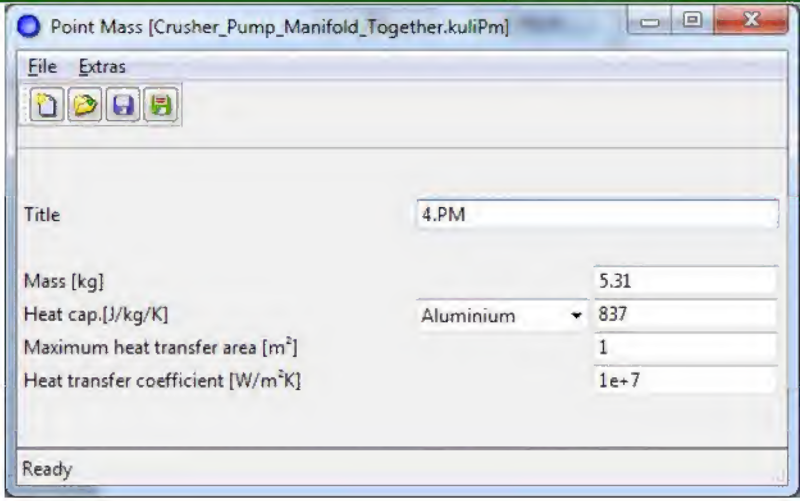
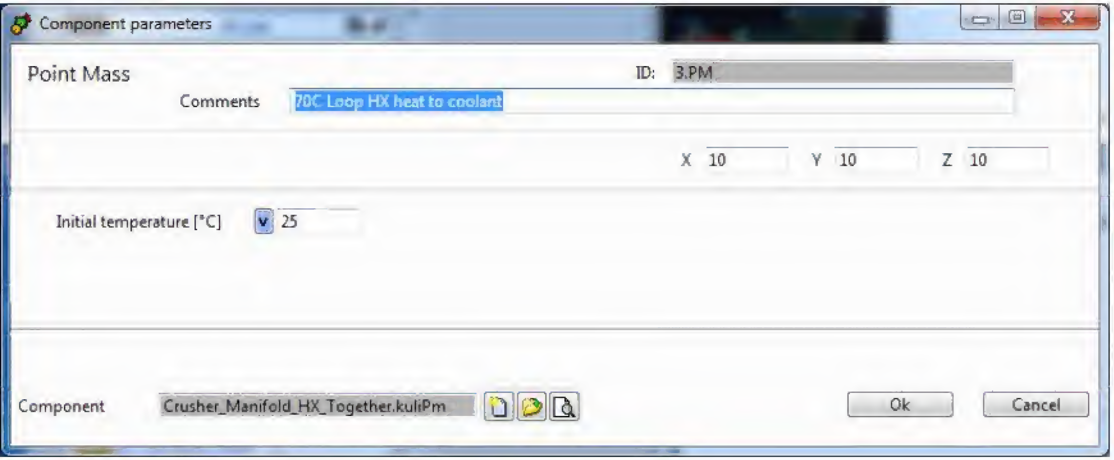
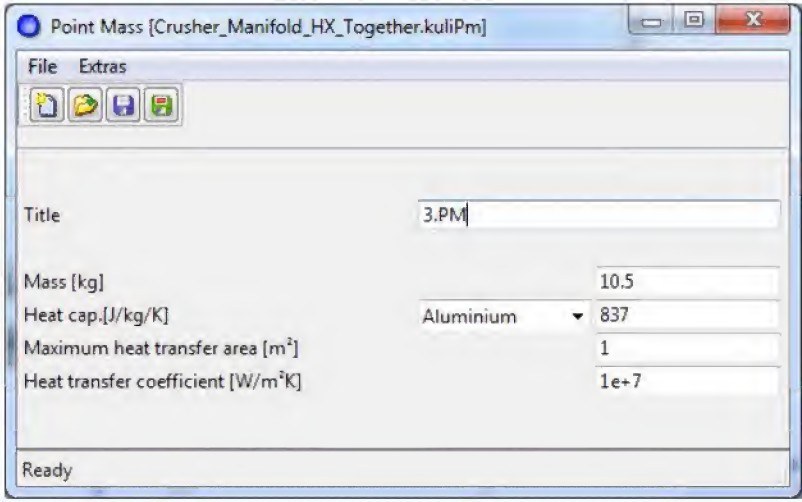
HX Point Mass









XV-2_Generator.kuliPu

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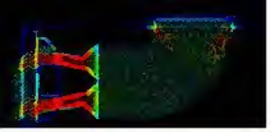
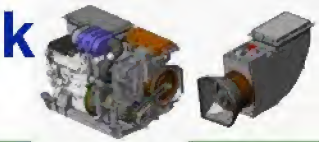
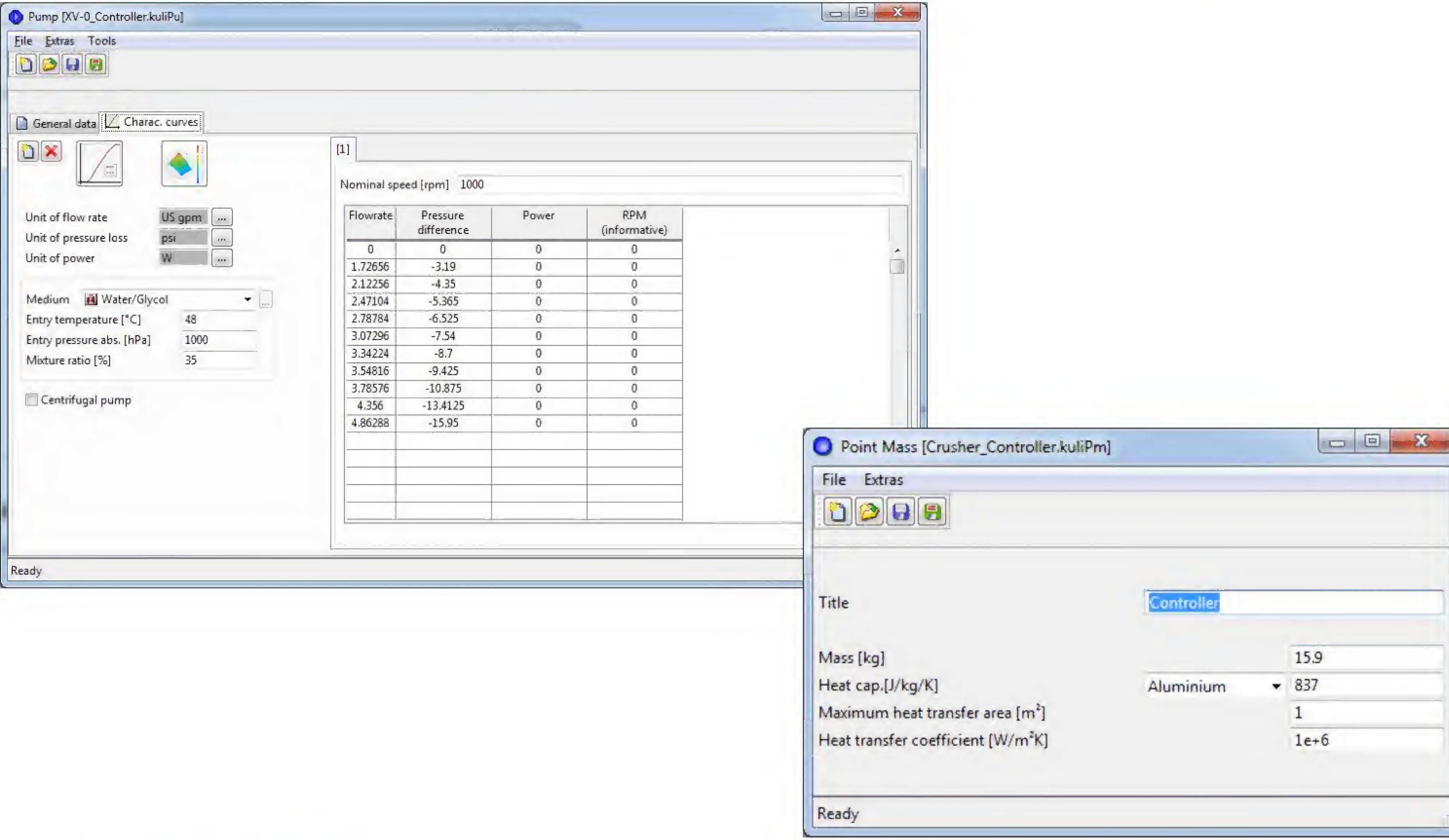


Motor/Gen1/Brake Chopper Controller Back Pressure & Point Mass (9 Controllers)





Flowrate	Pressure difference	Power	RPM (informative)
0	0	0	0
1.72656	-3.19	0	0
2.12256	-4.35	0	0
2.47104	-5.365	0	0
2.78784	-6.525	0	0
3.07296	-7.54	0	0
3.34224	-8.7	0	0
3.54816	-9.425	0	0
3.78576	-10.875	0	0
4.356	-13.4125	0	0
4.86288	-15.95	0	0

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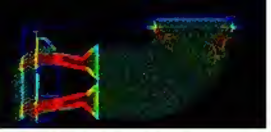
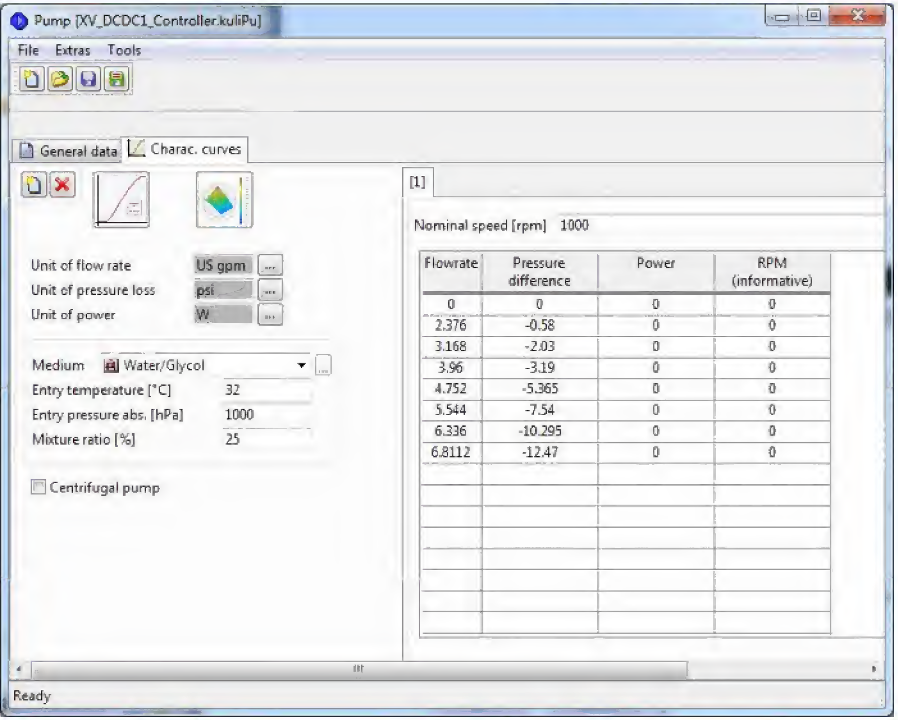


HV DC-DC Converter
Back Pressure & Point Mass


Pump [XV_DCDC1_Controller.kuliPu]

File Extras Tools

General data | Charac. curves

Unit of flow rate: US gpm
Unit of pressure loss: psi
Unit of power: W

Medium: Water/Glycol
Entry temperature [°C]: 32
Entry pressure abs. [hPa]: 1000
Mixture ratio [%]: 25

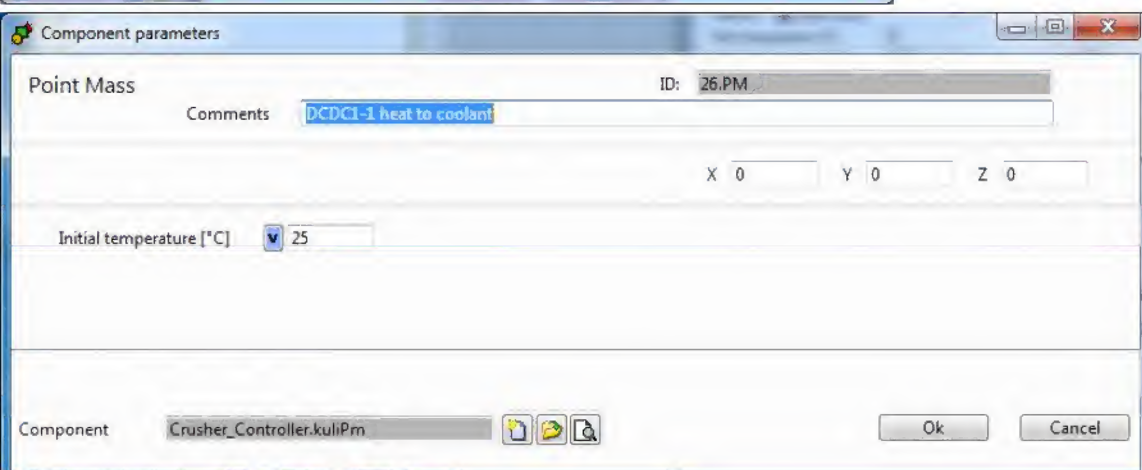
Centrifugal pump

[1]

Nominal speed [rpm]: 1000

Flowrate	Pressure difference	Power	RPM (informative)
0	0	0	0
2.376	-0.58	0	0
3.168	-2.03	0	0
3.96	-3.19	0	0
4.752	-5.365	0	0
5.544	-7.54	0	0
6.336	-10.295	0	0
6.8112	-12.47	0	0

Ready


Component parameters

Point Mass ID: 26.PM

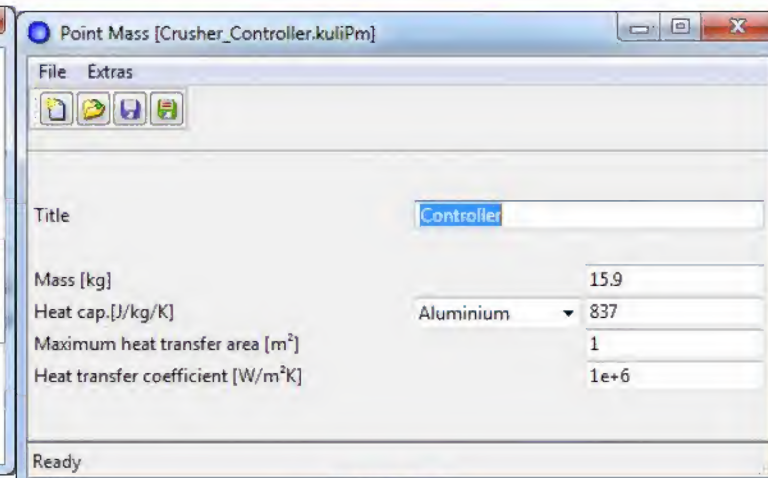
Comments: DCDC1-1 heat to coolant

X 0 Y 0 Z 0

Initial temperature [°C]: 25

Component: Crusher_Controller.kuliPm

Ok Cancel

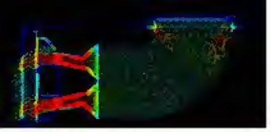

Point Mass [Crusher_Controller.kuliPm]

File Extras

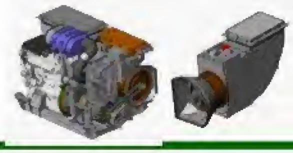
Title: Controller

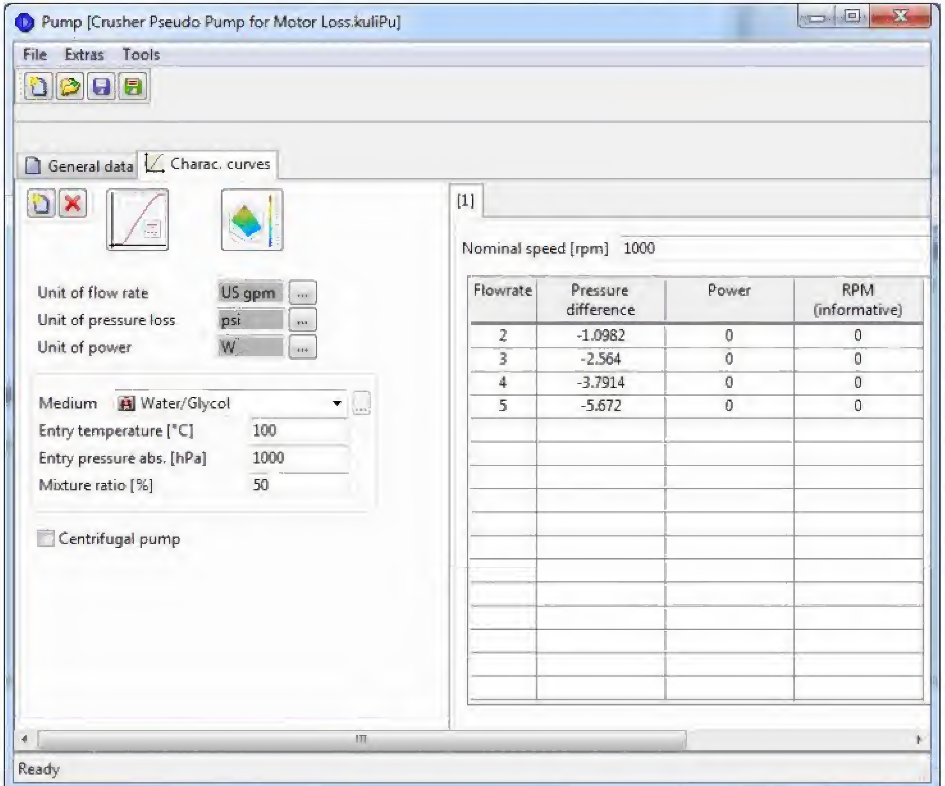
Mass [kg]: 15.9
Heat cap.[J/kg/K]: Aluminium 837
Maximum heat transfer area [m²]: 1
Heat transfer coefficient [W/m²K]: 1e+6

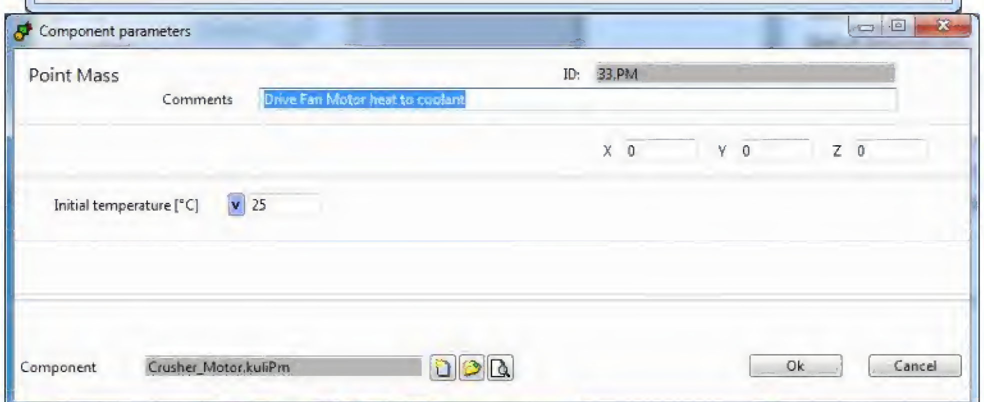
Ready

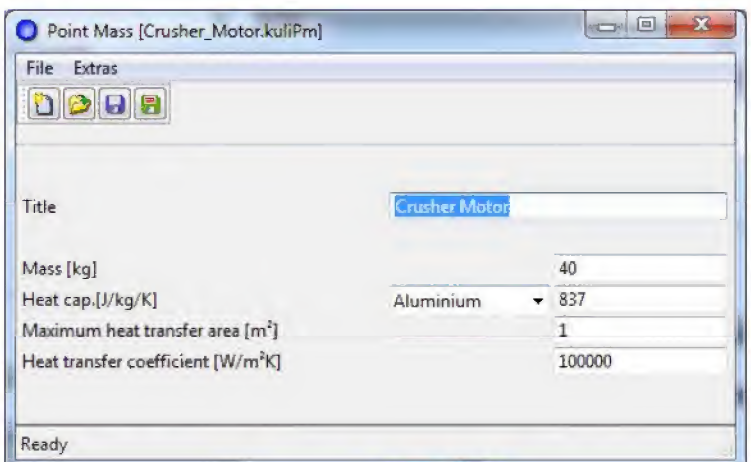


Drive Snake Fan Motor
Back Pressure & Point Mass

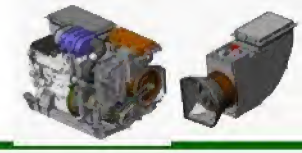


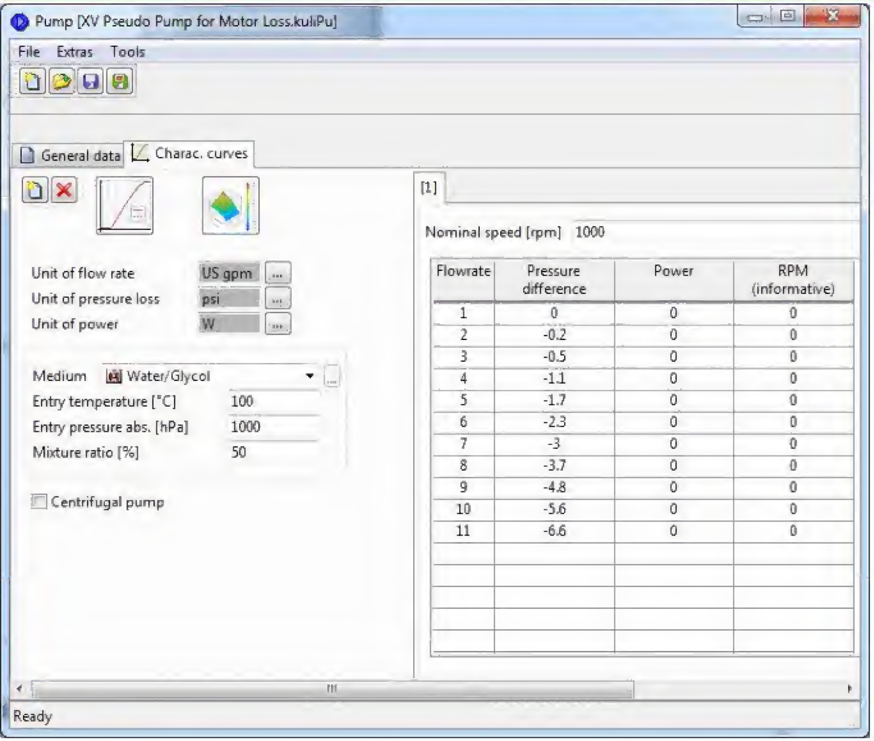


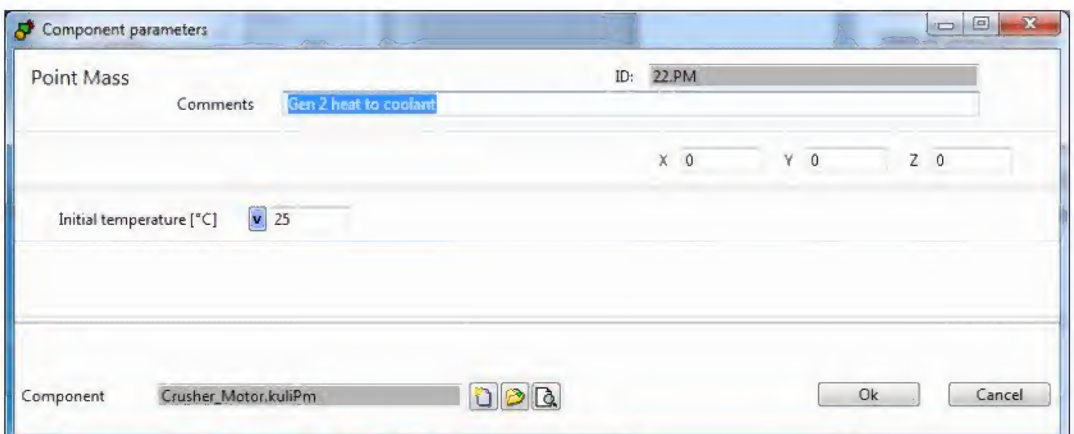


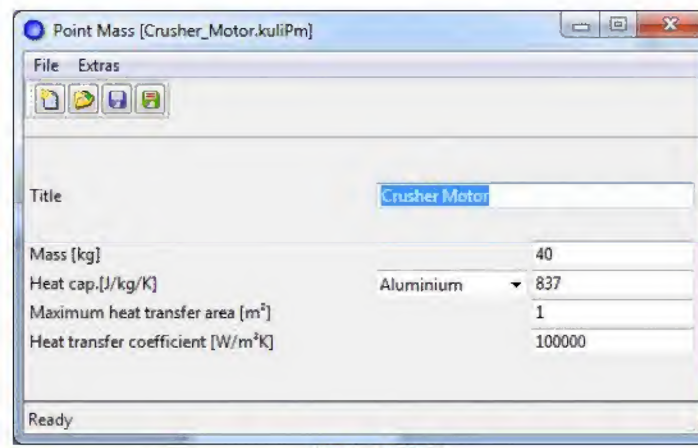


Engine Snake Fan Motor/MV Gen Back Pressure & Point Mass

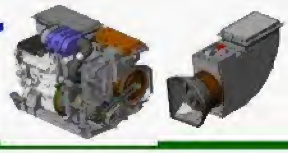


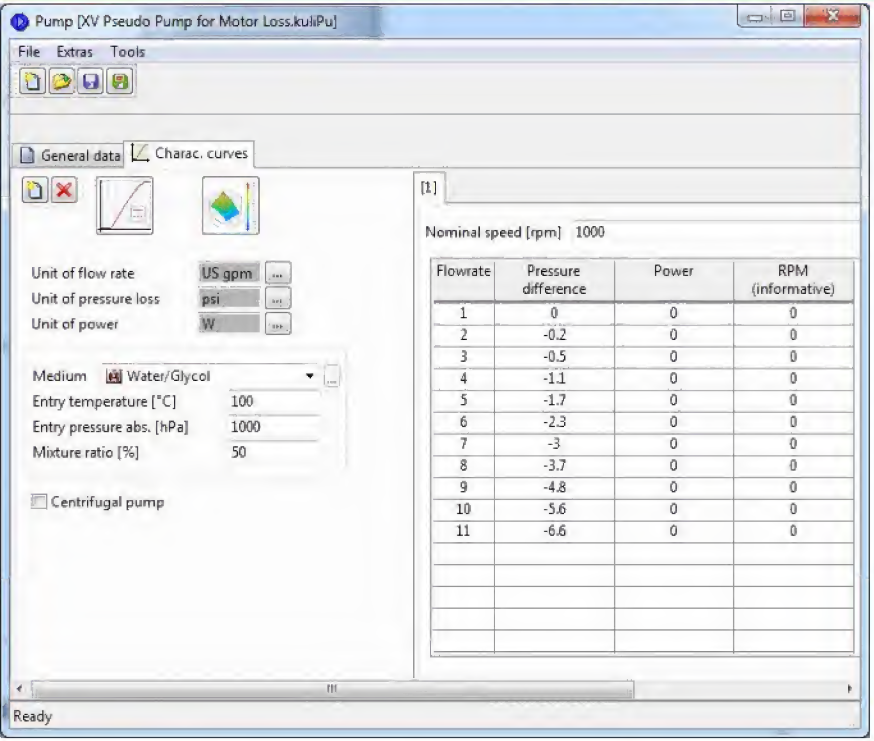






Engine Snake Fan Motor/MV Gen Controller Back Pressure & Point Mass





Pump [XV Pseudo Pump for Motor Loss.kuliPu]

File Extras Tools

General data | Charac. curves

Unit of flow rate: US gpm
Unit of pressure loss: psi
Unit of power: W

Medium: Water/Glycol
Entry temperature [°C]: 100
Entry pressure abs. [hPa]: 1000
Mixture ratio [%]: 50

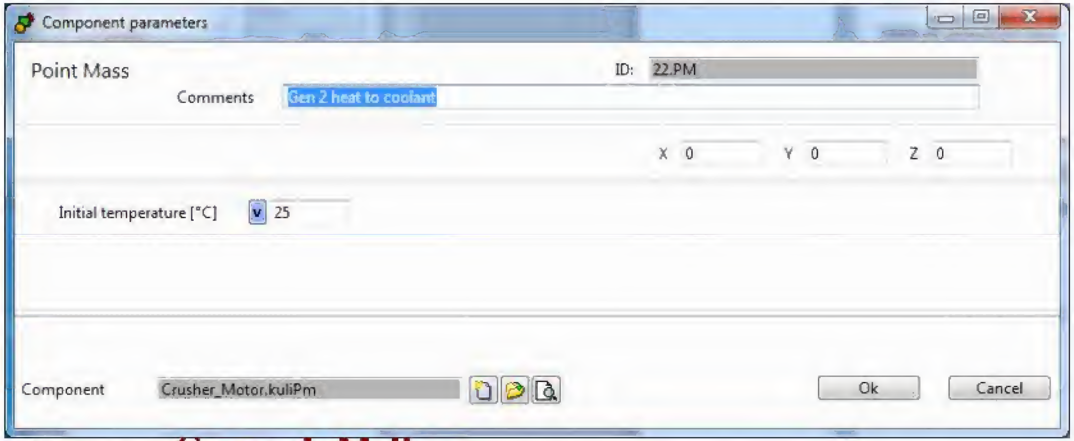
Centrifugal pump

[1]

Nominal speed [rpm]: 1000

Flowrate	Pressure difference	Power	RPM (informative)
1	0	0	0
2	-0.2	0	0
3	-0.5	0	0
4	-1.1	0	0
5	-1.7	0	0
6	-2.3	0	0
7	-3	0	0
8	-3.7	0	0
9	-4.8	0	0
10	-5.6	0	0
11	-6.6	0	0

Ready



Component parameters

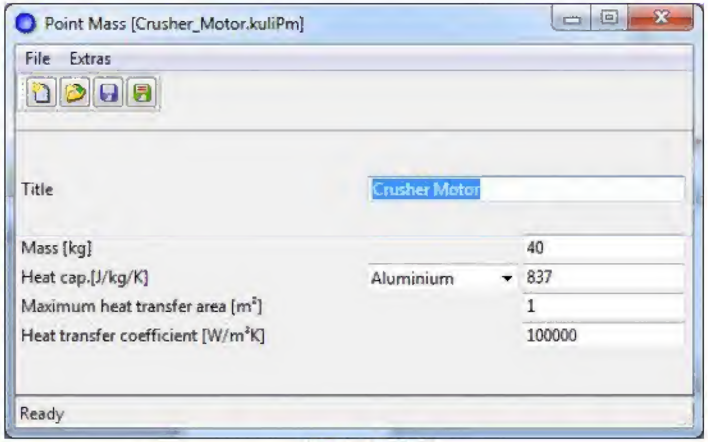
Point Mass ID: 22.PM
Comments: Gen 2 heat to coolant

X 0 Y 0 Z 0

Initial temperature [°C]: v 25

Component: Crusher_Motor.kuliPm

Ok Cancel



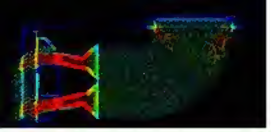
Point Mass [Crusher_Motor.kuliPm]

File Extras

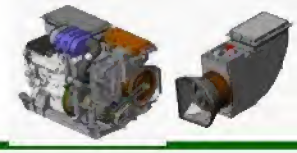
Title: Crusher Motor

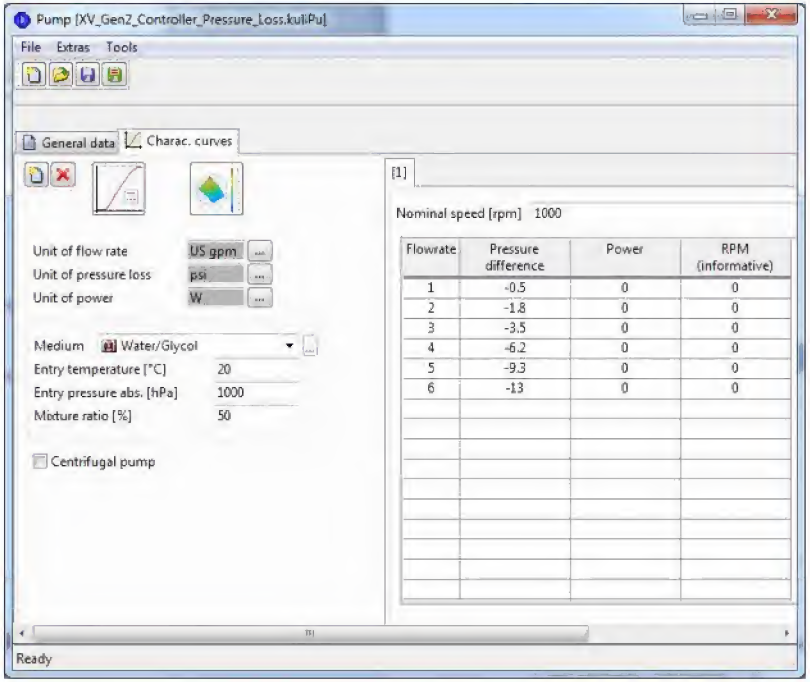
Mass [kg]: 40
Heat cap.[J/kg/K]: Aluminium 837
Maximum heat transfer area [m²]: 1
Heat transfer coefficient [W/m²K]: 100000

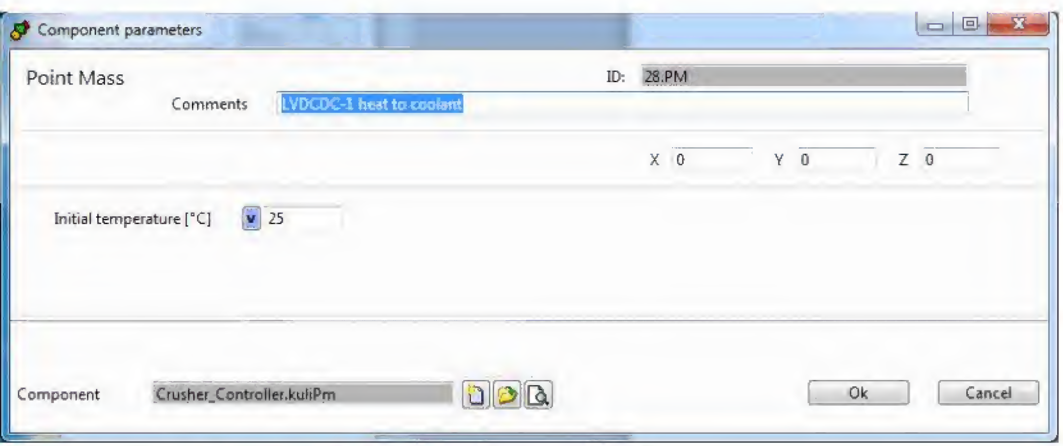
Ready

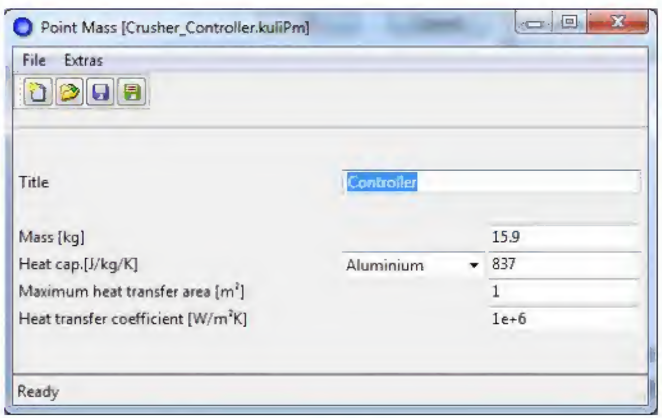


LV DC-DC Converter
Back Pressure & Point Mass









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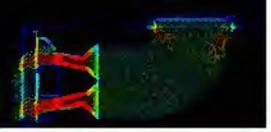

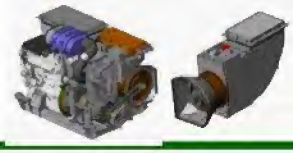

Sub-Ambient Loop

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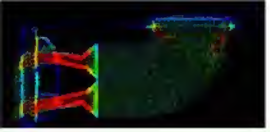
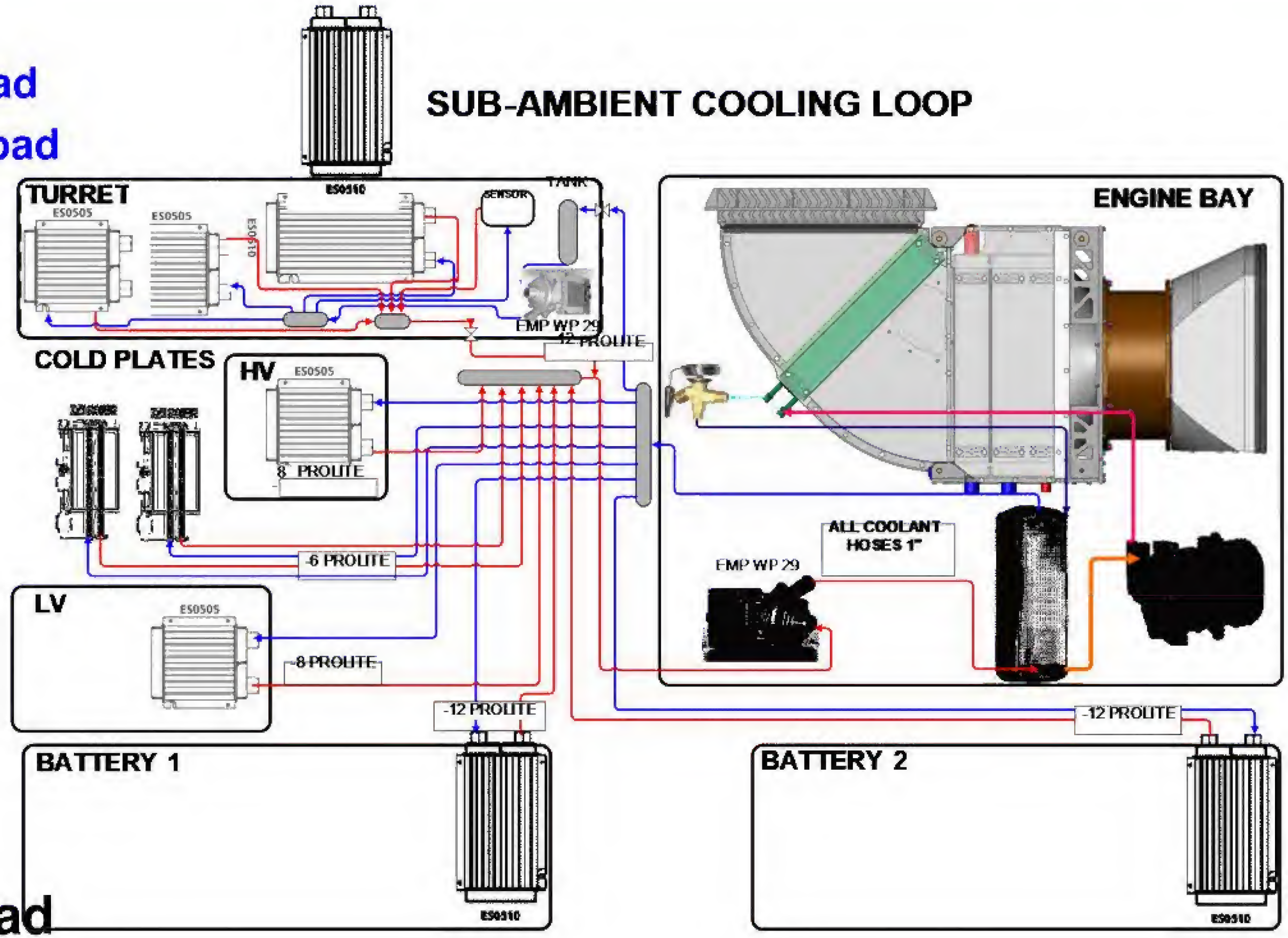
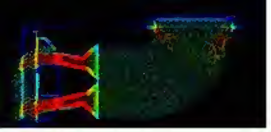
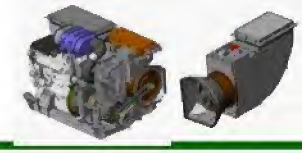


XV – Sub-Ambient Loop

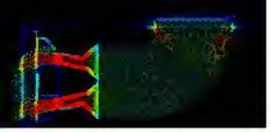
- Capacity
  - → Max Eqpt & Vehicle Load
  - → 45C ambient w/ Solar load
- Air over heat xchg
  - → Turret = all mission equipment
  - → LV = LV PDU
  - → HV = HV PDU
  - → Battery Packs
- Cold plates = Ctrls
  - → Drive Snake Fan
  - → Compressor
- 2nd Turret – no eqpt
- Model ~ actual - full load
- Some margin in sub-ambient



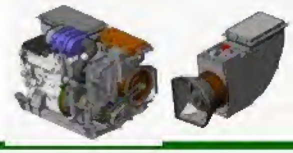




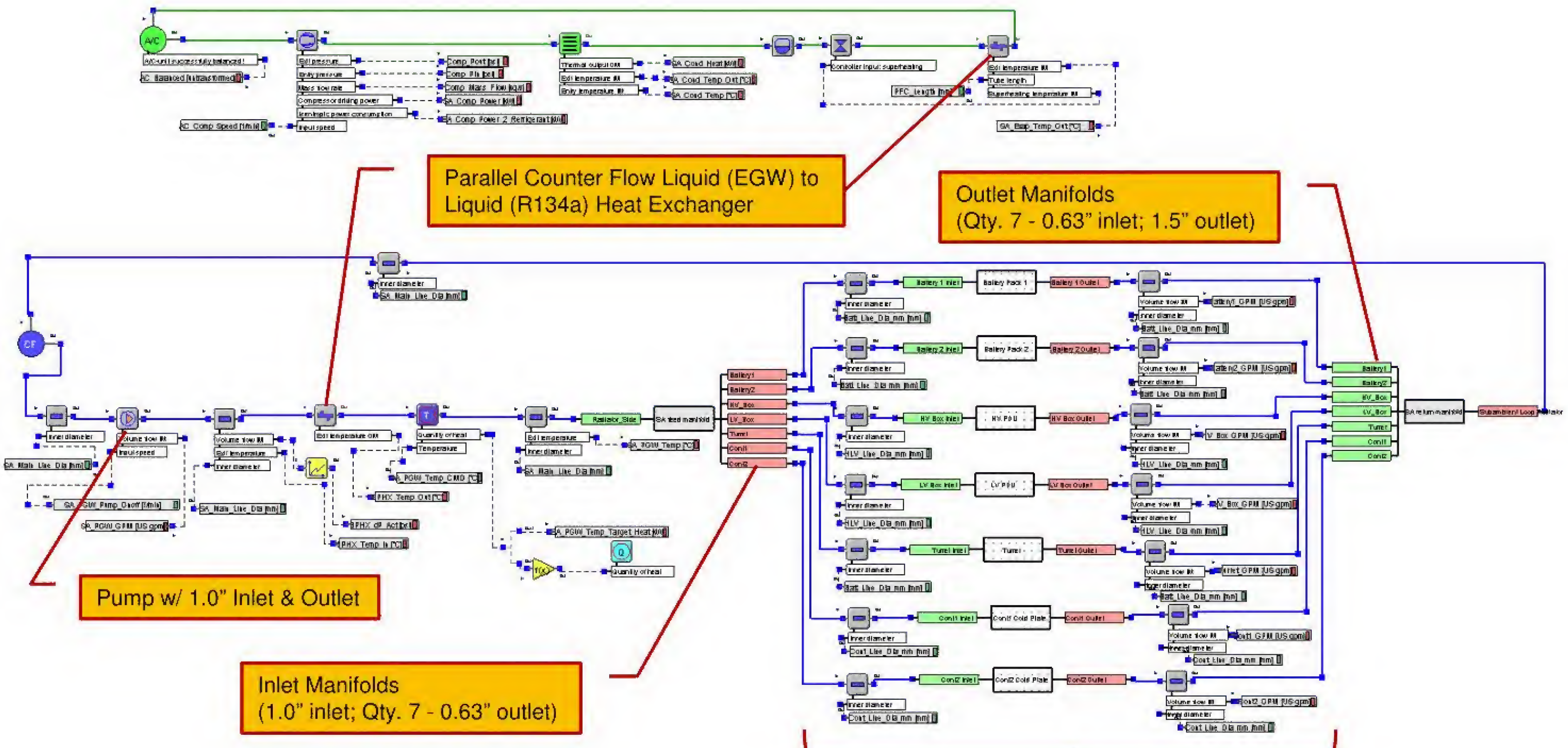
Sub-Ambient Loop – EGW Side



Kuli Sub-ambient Loop

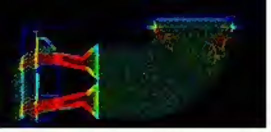


- **HVAC Loop**

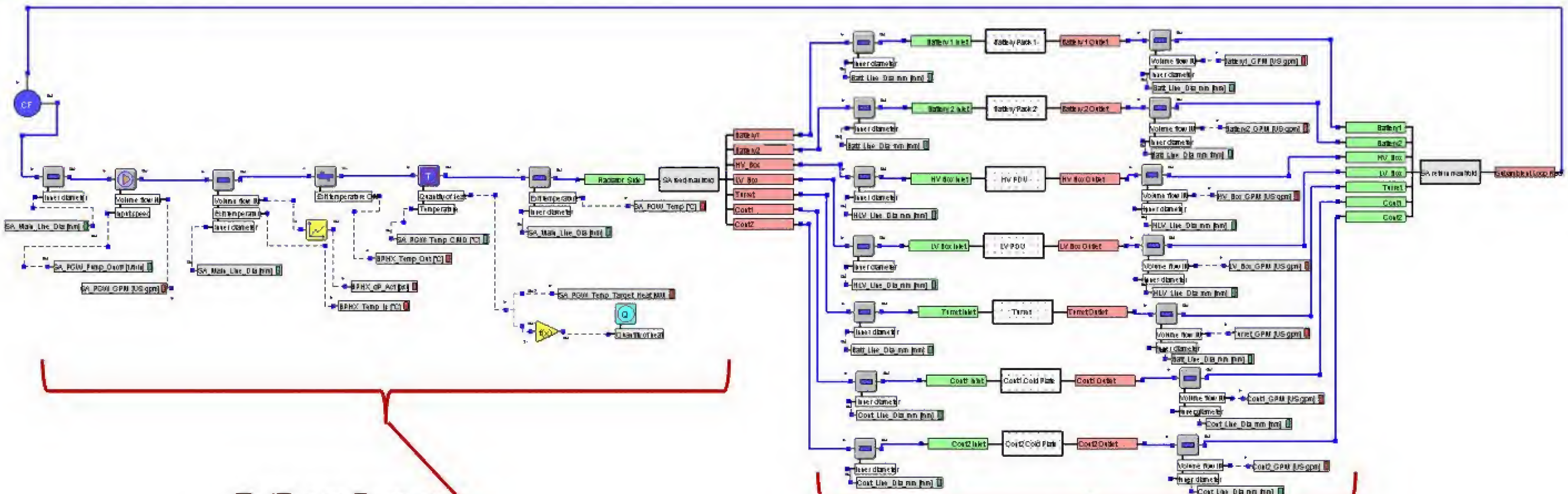


7 ea. parallel equipment coolant branches (all hoses 0.63" ID)

Equipment model = See next slide



Kuli Sub-ambient Loop - Hoses



To/From Pumps

To/From Equipment

ID = 25.4 mm						ID = 16 mm			
Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)	Tube #	Length (mm)
						212	762	219	762
						206	1016	213	1016
						207	1702	334	1702
222	889	221	152	220	1778	208	3150	215	3150
						209	2540	216	2540
						210	1956	217	1956
						211	1956	218	1956

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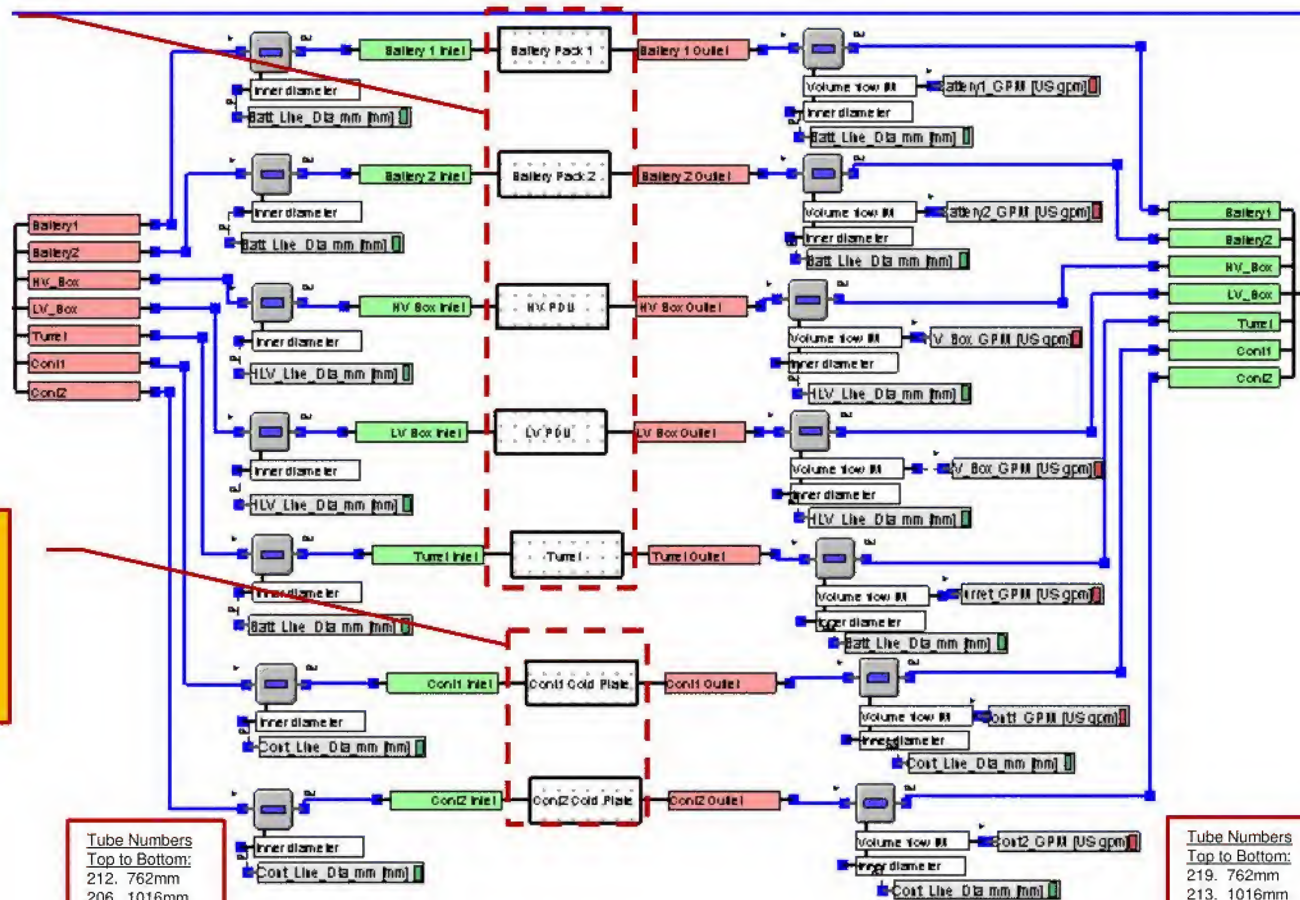
Kuli Sub-ambient Loop

- **Sub-ambient EGW loop – 2 types of component heat exchangers**

Heat & Liquid to Air HX (fans blow air over heat exchanger then into equipment enclosure)
Battery Packs (2)
HV Rack
LV Rack
Turret (equipment rack)

Heat & Cold Plate HX (heat exchanger embedded in equipment mounting plate – conduction)
Drive Snake Fan Controller
SA Compressor Motor Controller



Tube Numbers
Top to Bottom:
212. 762mm
206. 1016mm
207. 1701.8mm
208. 3149.6mm
209. 2540mm
210. 1955.8mm
211. 1955.8mm

Tube Numbers
Top to Bottom:
219. 762mm
213. 1016mm
214. 1701.8mm
215. 3149.6mm
216. 3454.4mm
217. 1955.9mm
218. 1955.8mm

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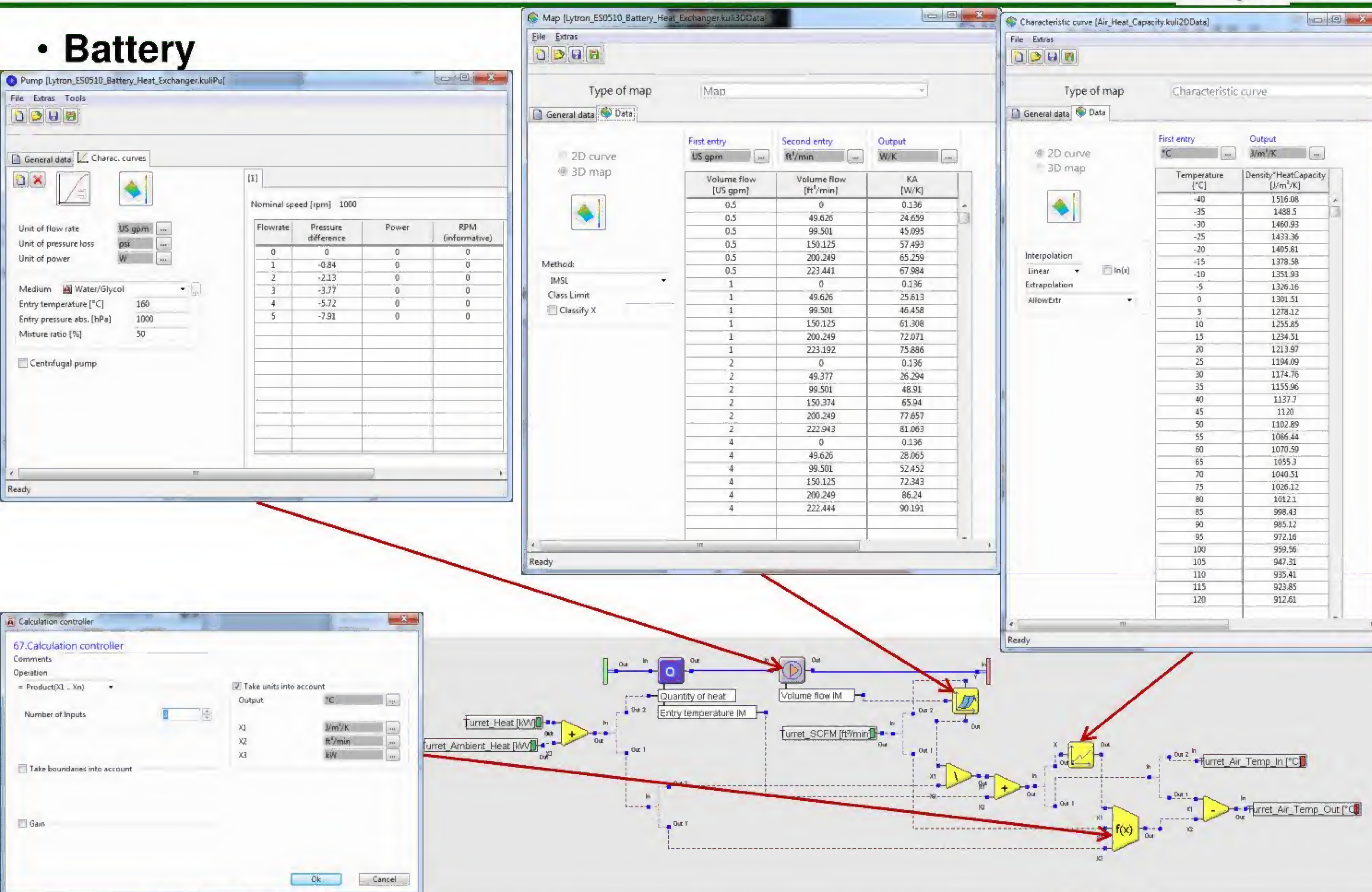
Kuli Sub-ambient Loop – Battery X 2

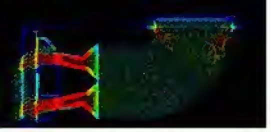
- **Battery**



Flowrate	Pressure difference	Power	RPM (informative)
0	0	0	0
1	-0.84	0	0
2	-2.13	0	0
3	-3.77	0	0
4	-5.72	0	0
5	-7.91	0	0

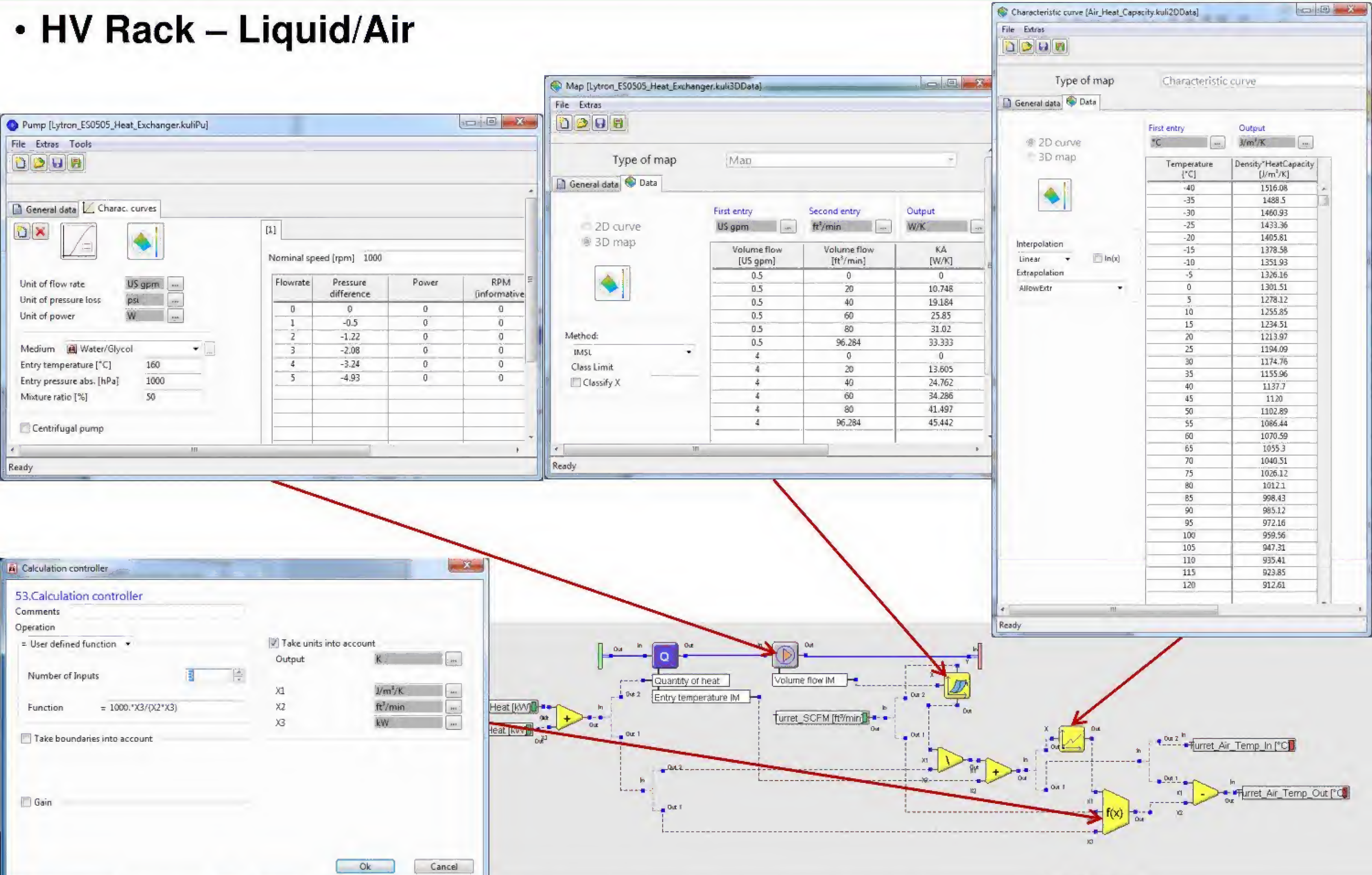
Volume flow [US gpm]	Volume flow [ft³/min]	KA [W/K]
0.5	0	0.136
0.5	49.626	24.659
0.5	99.501	45.095
0.5	150.125	57.493
0.5	200.249	65.259
0.5	223.441	67.984
1	0	0.136
1	49.626	25.613
1	99.501	46.458
1	150.125	61.308
1	200.249	72.071
1	223.192	75.886
2	0	0.136
2	49.377	26.294
2	99.501	48.91
2	150.374	65.94
2	200.249	77.657
2	222.943	81.063
4	0	0.136
4	49.626	28.065
4	99.501	52.452
4	150.125	72.343
4	200.249	86.24
4	222.444	90.191

Temperature [°C]	Density*HeatCapacity [J/m³/K]
-40	1516.08
-35	1488.5
-30	1460.93
-25	1433.36
-20	1405.81
-15	1378.58
-10	1351.93
-5	1326.16
0	1301.51
5	1278.12
10	1255.85
15	1234.51
20	1213.97
25	1194.09
30	1174.76
35	1155.96
40	1137.7
45	1120
50	1102.89
55	1086.44
60	1070.59
65	1055.3
70	1040.51
75	1026.12
80	1012.1
85	998.43
90	985.12
95	972.16
100	959.56
105	947.31
110	935.41
115	923.85
120	912.61



Kuli Sub-ambient Loop – HV Rack

- **HV Rack – Liquid/Air**



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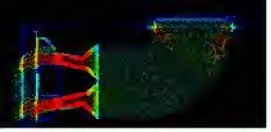
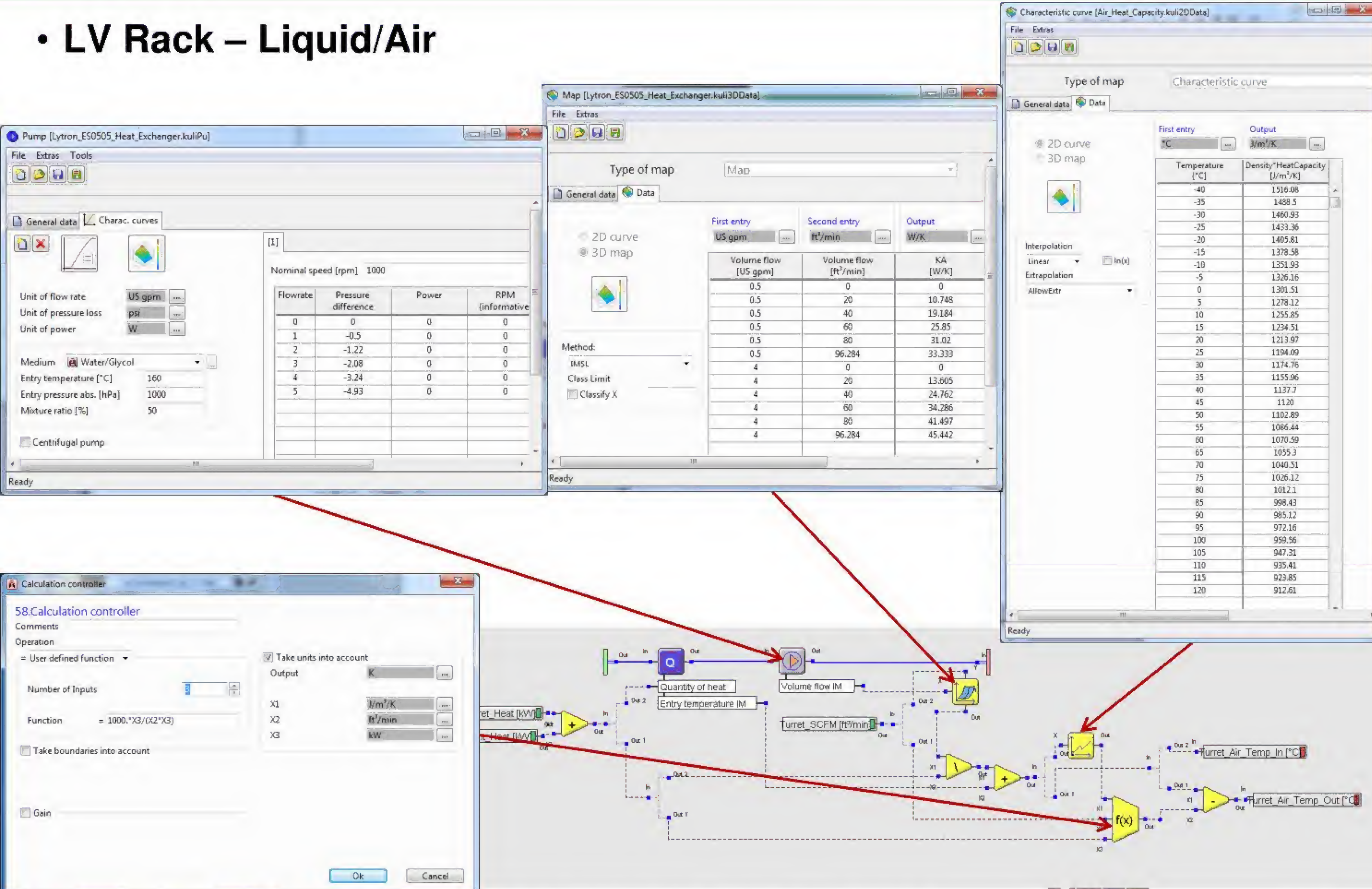
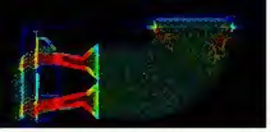


Kuli Sub-ambient Loop – LV Rack

- **LV Rack – Liquid/Air**

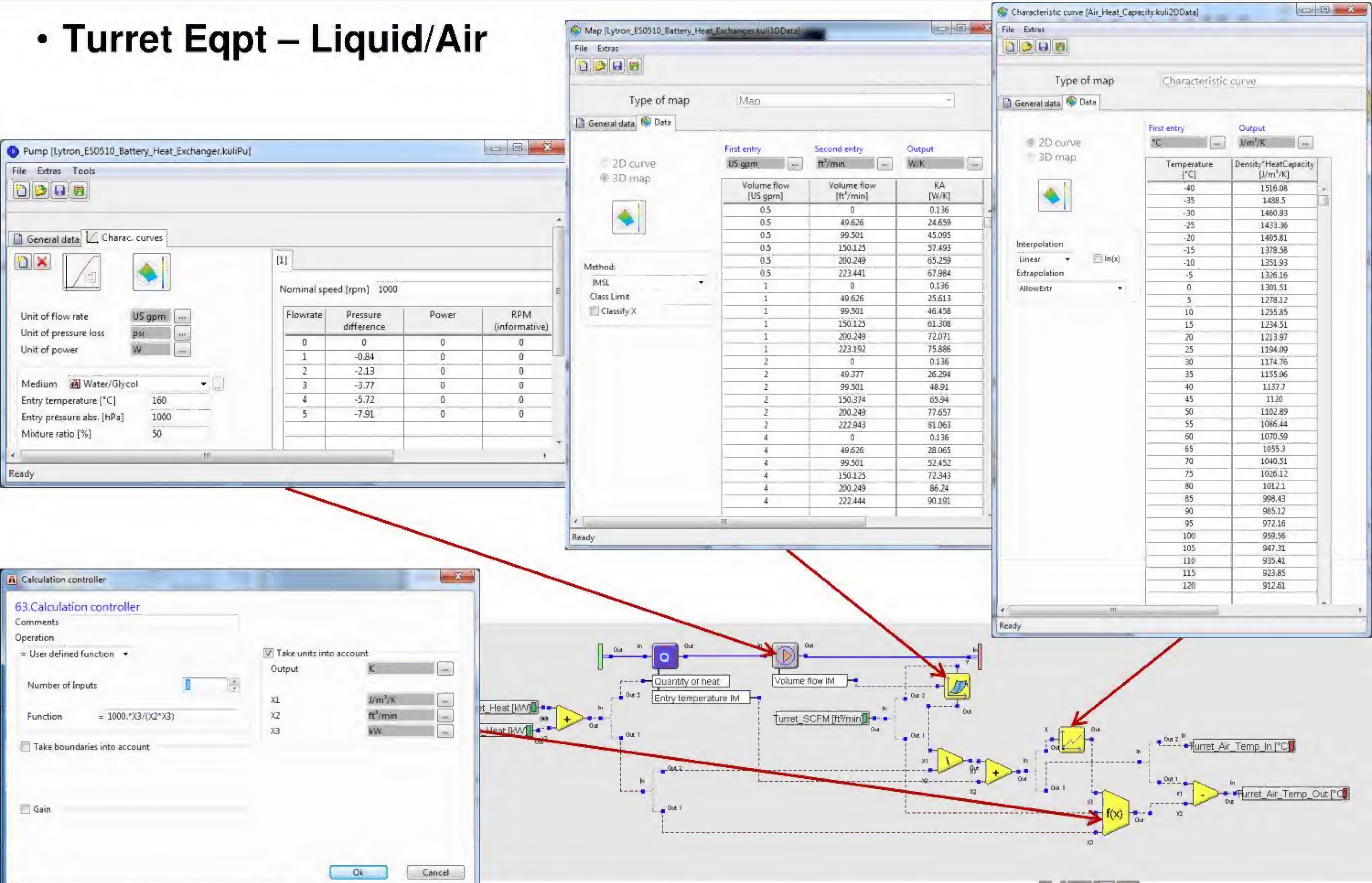


NREC ENGINEERING CENTER



Kuli Sub-ambient Loop – Turret

- **Turret Eqpt – Liquid/Air**



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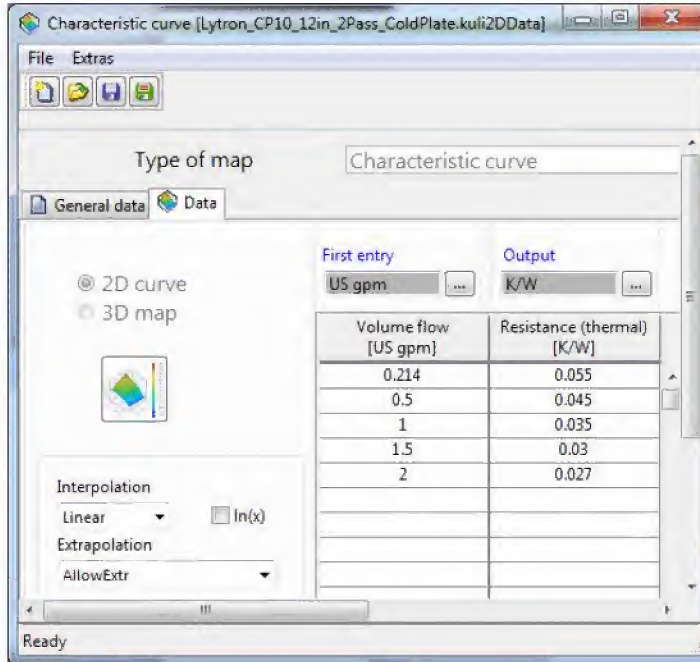
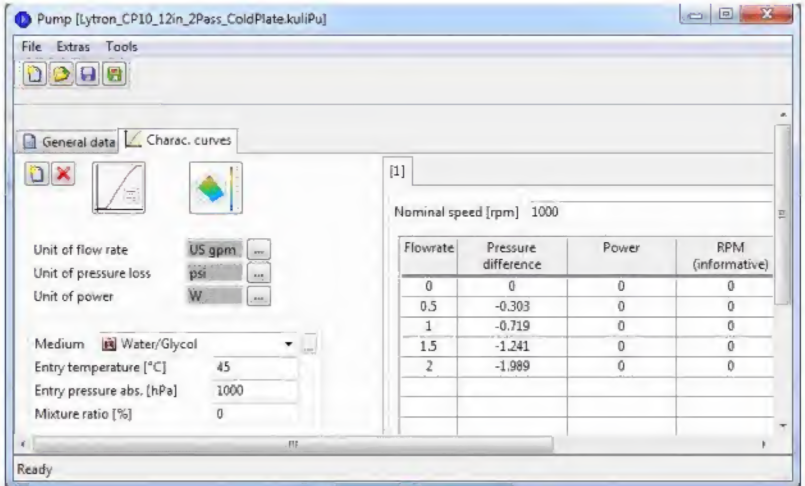
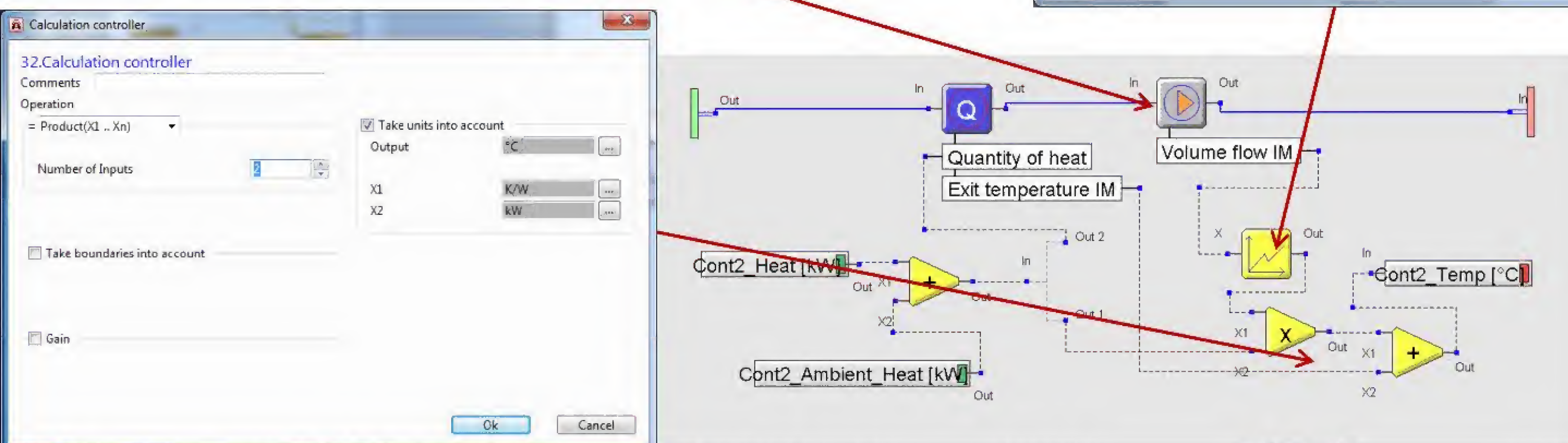
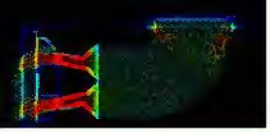
Kuli Sub-ambient Loop – Cont 1 & 2

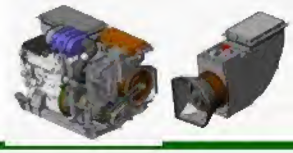
- **Drive Snake Fan & SA Compressor Motor Controllers HX– Liquid/Liquid**



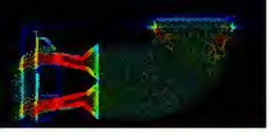




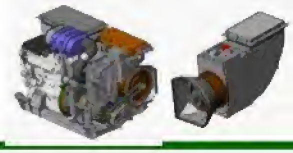




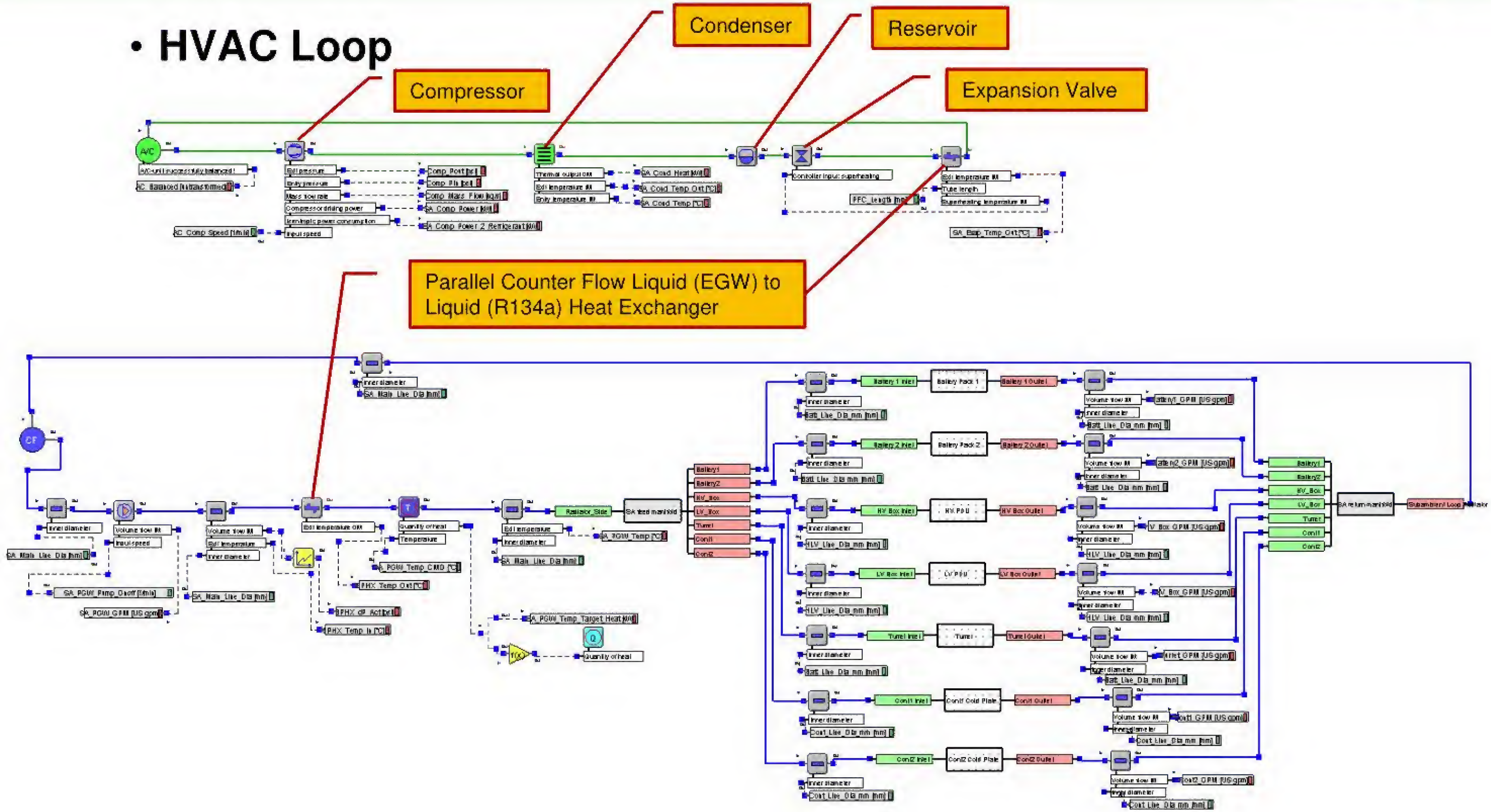
Sub-Ambient Loop – R134a Side

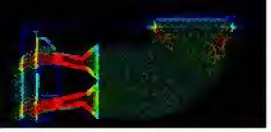


Kuli Sub-ambient Loop

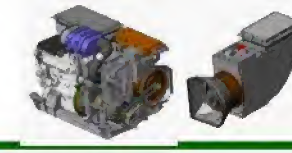


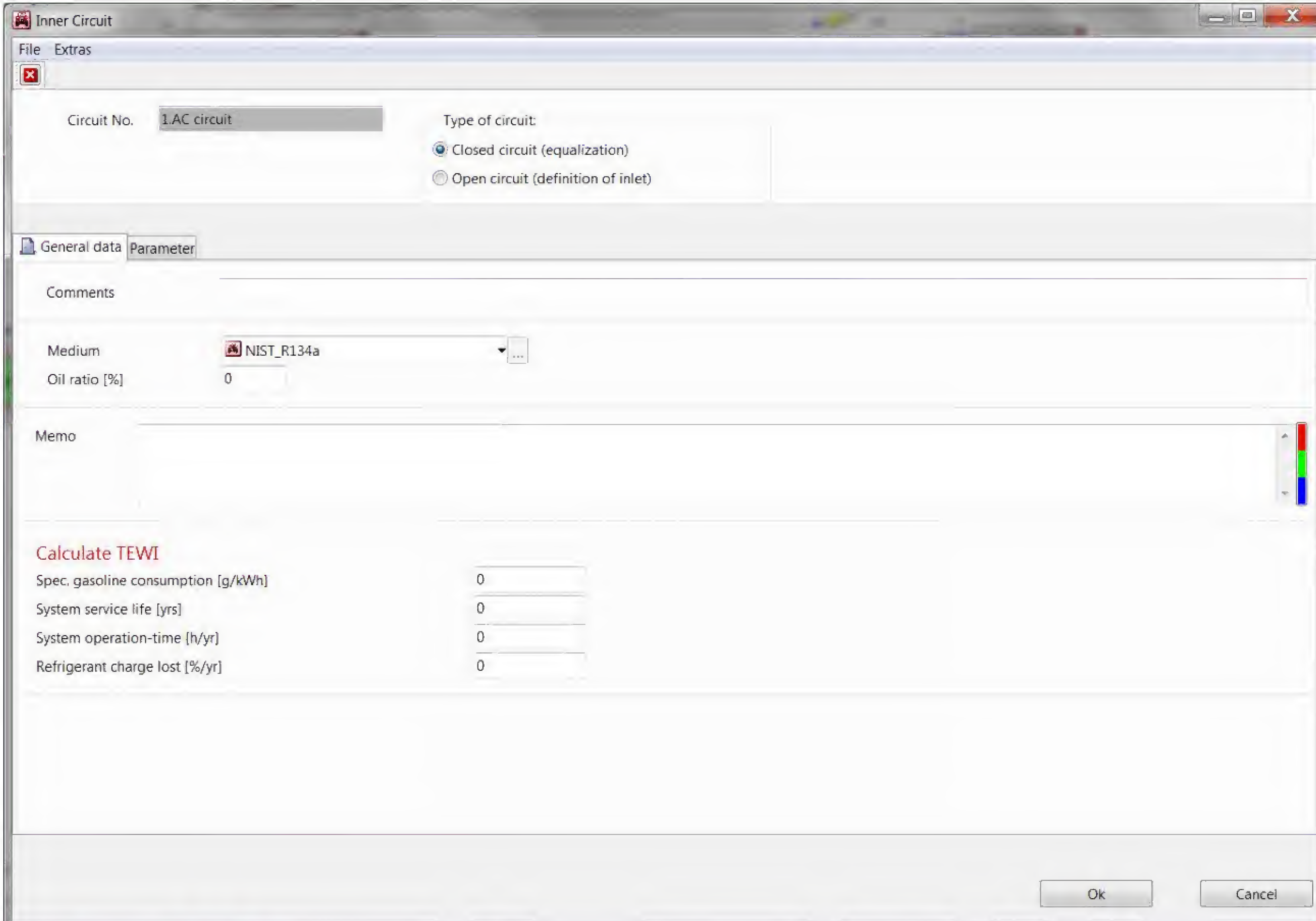
- **HVAC Loop**



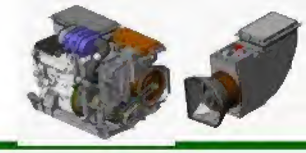


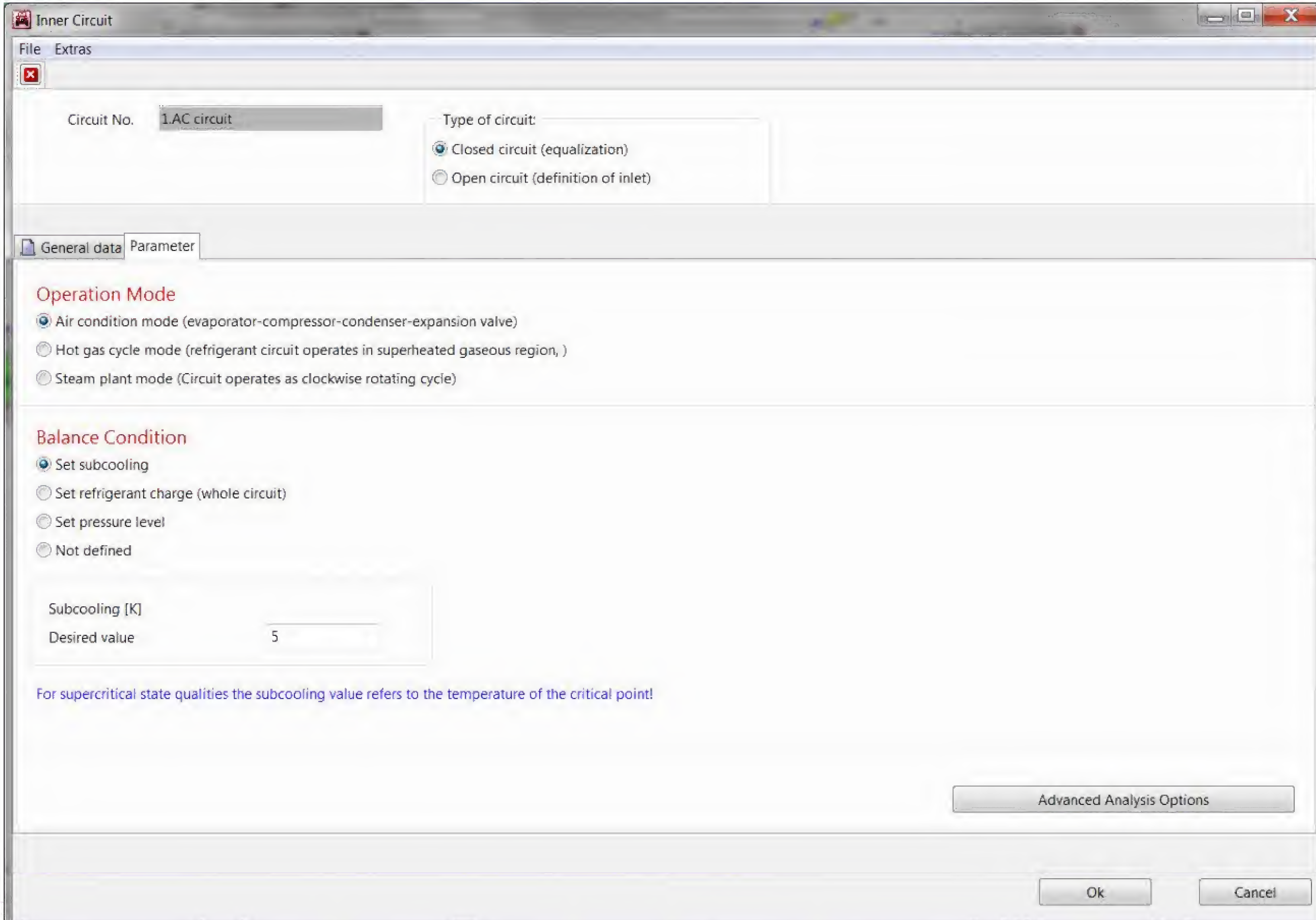
1.AC Circuit: General data

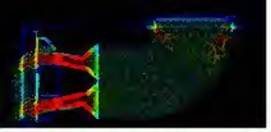




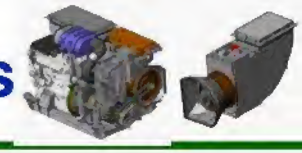
1.AC Circuit: Parameter

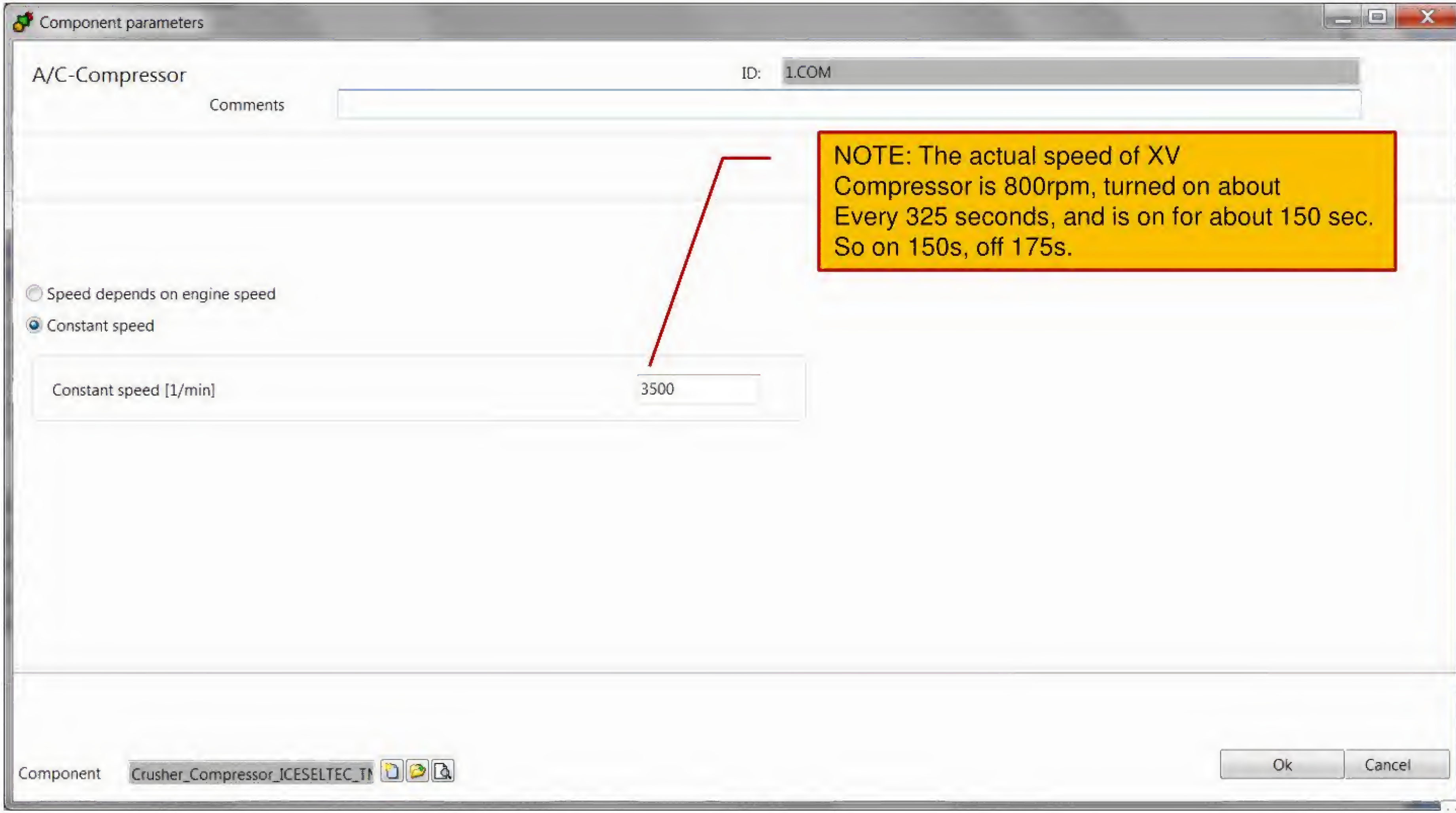






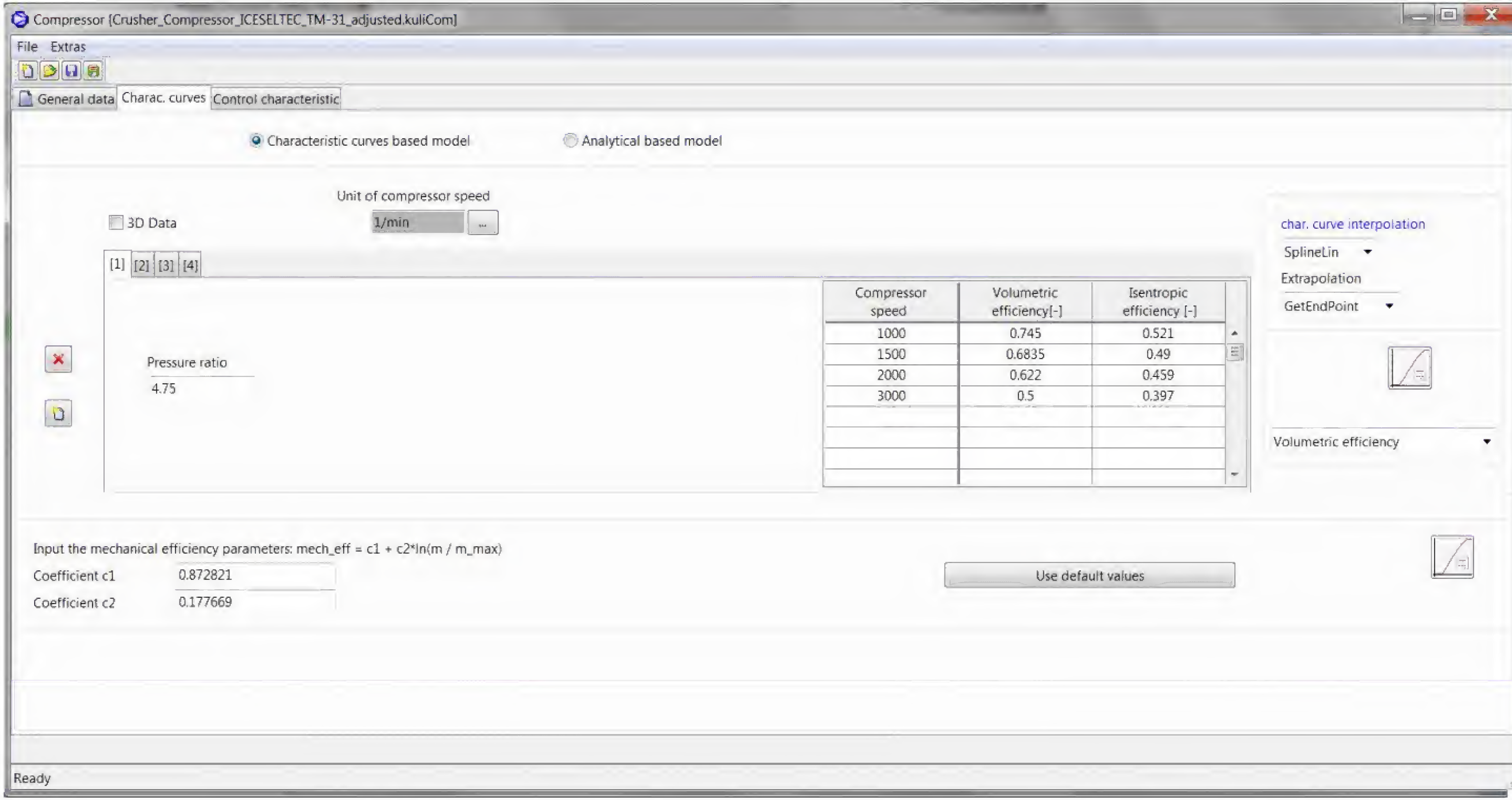
1.A/C-Compressor: Component parameters



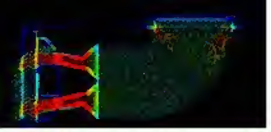


Crusher_Compressor_ICESELTEC_TM-31_adjusted.kuliCom

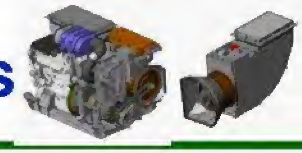
1.A/C-Compressor: Component parameters

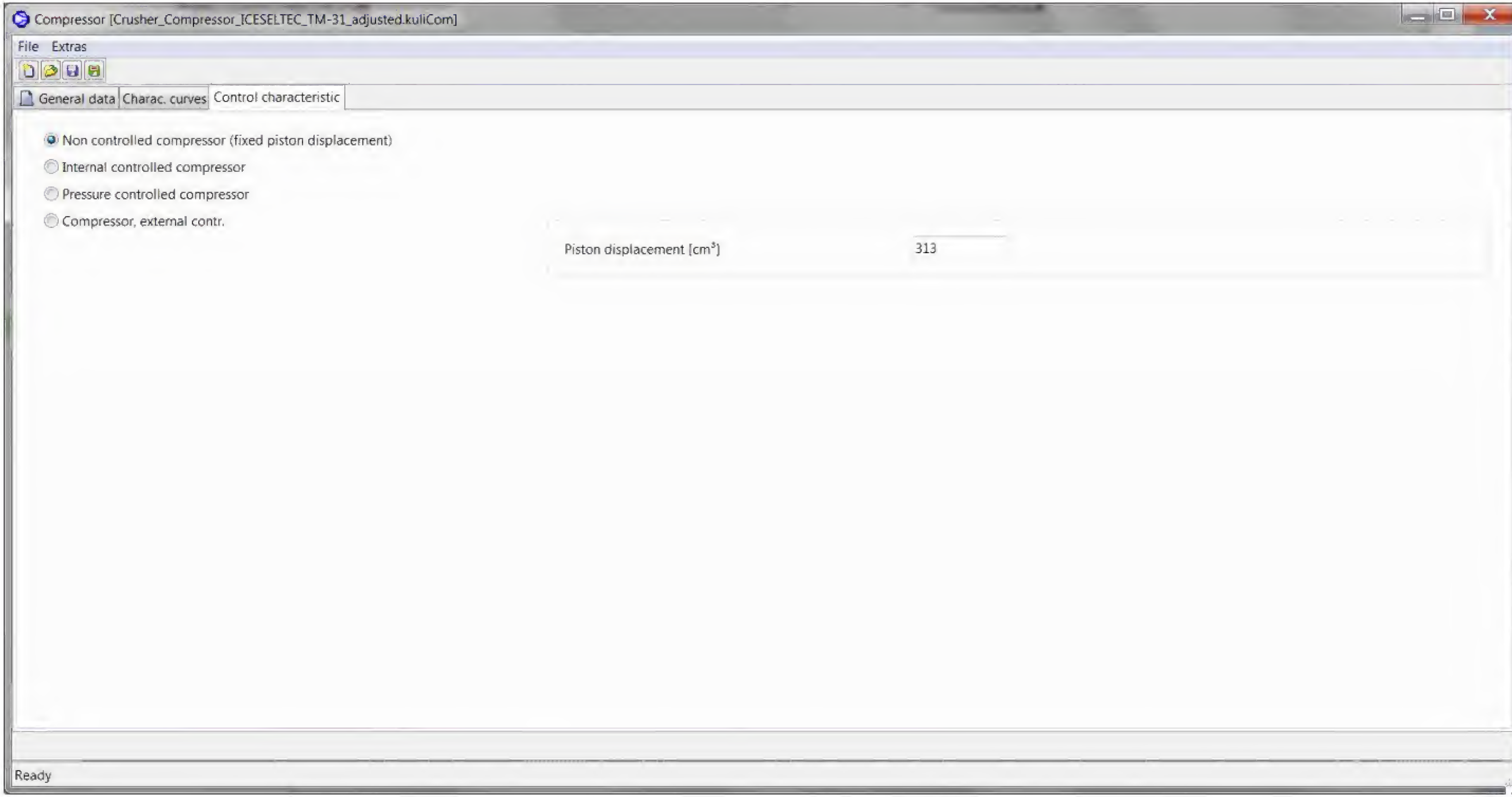


Crusher_Compressor_ICESELTEC_TM-31_adjusted.kuliCom

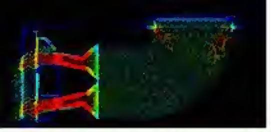


1.A/C-Compressor: Component parameters

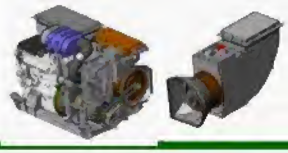


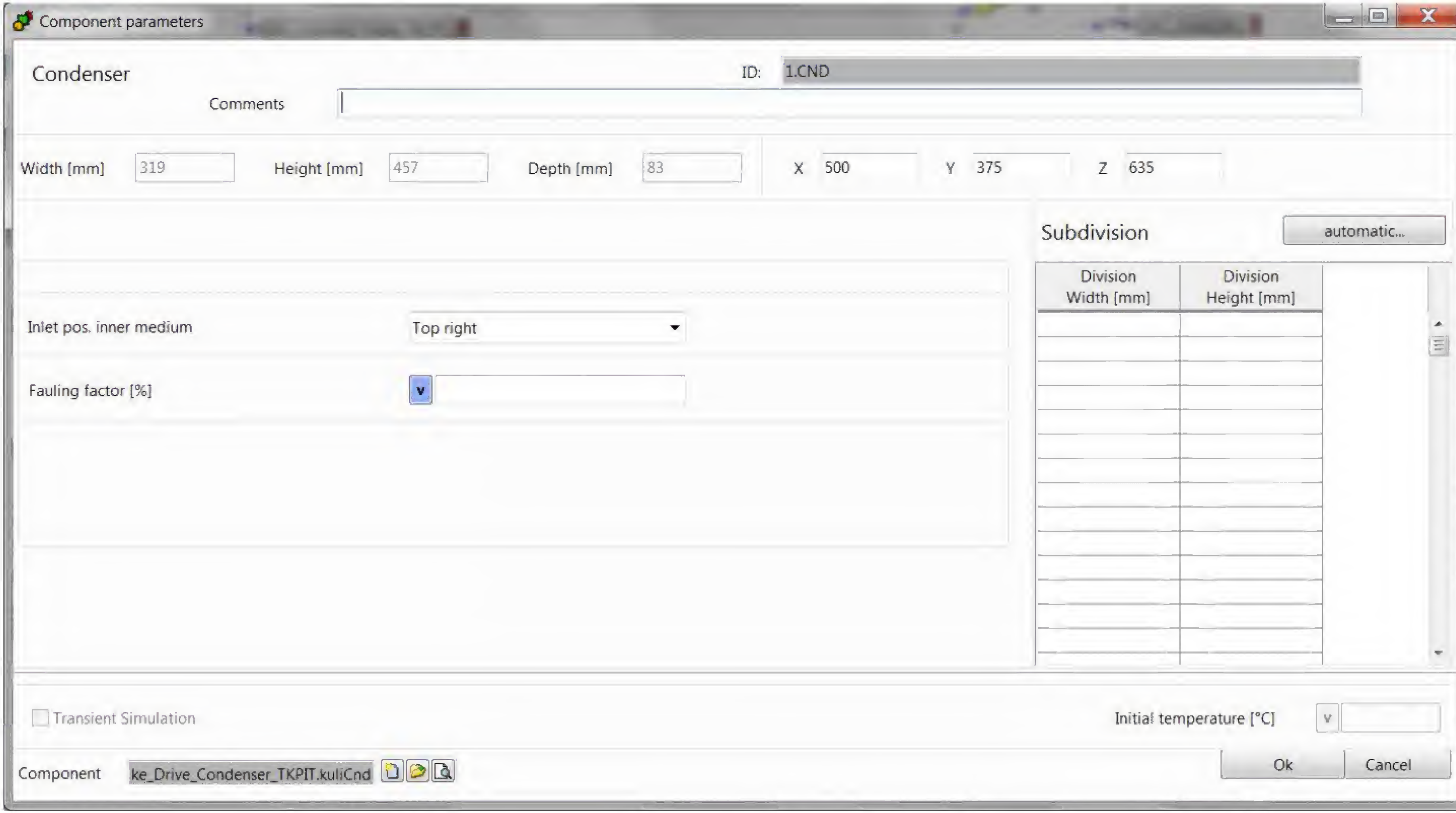


Crusher_Compressor_ICESELTEC_TM-31_adjusted.kuliCom

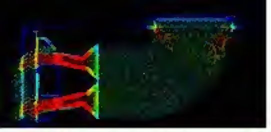


1.Condensor: Component parameters

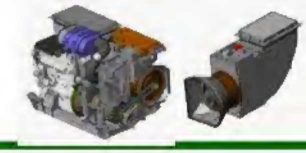


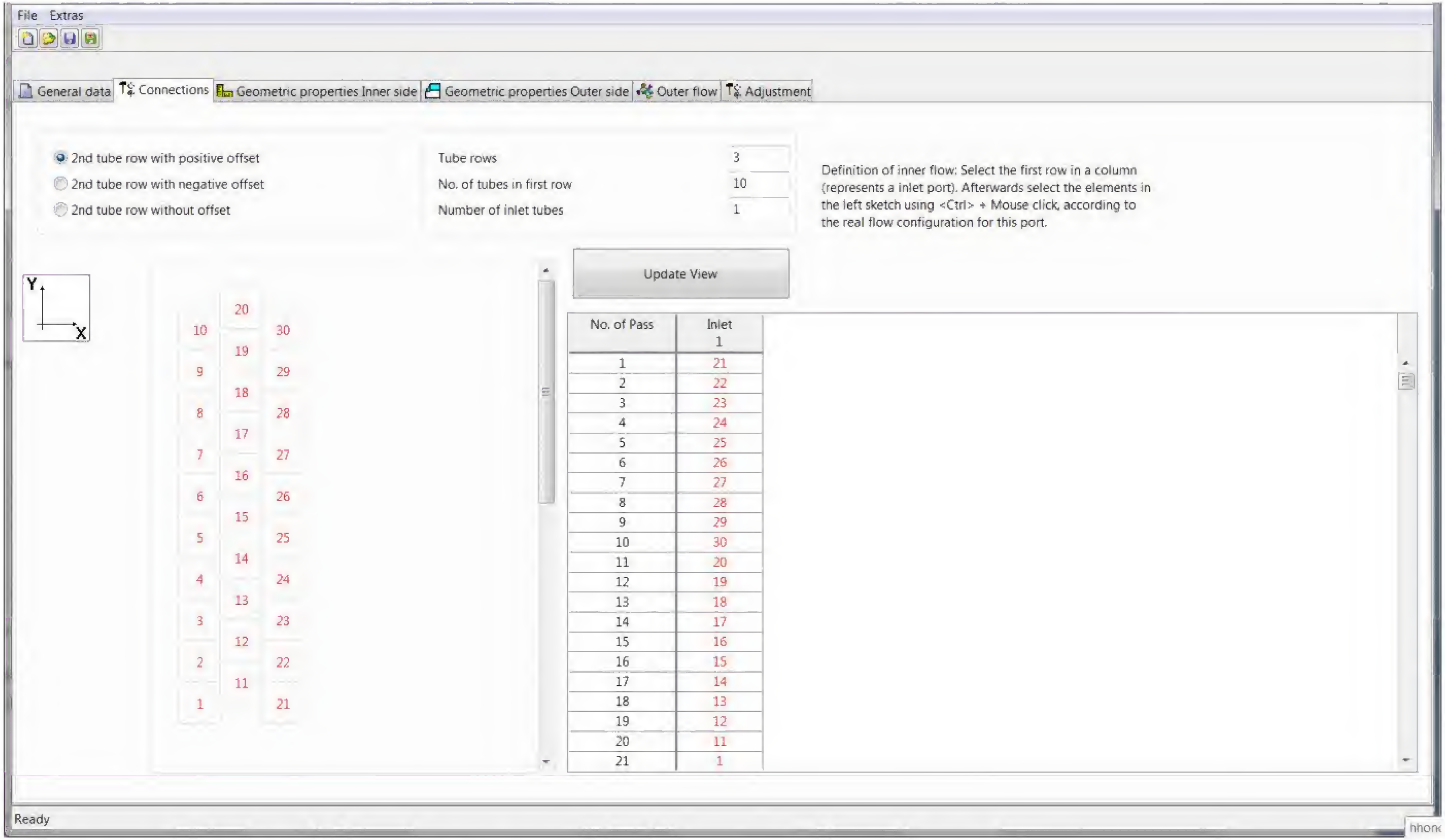


XV_Snake_Drive_Condenser_TKPIT.kuliCnd

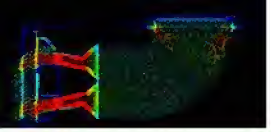


1.Condensor: Component parameters

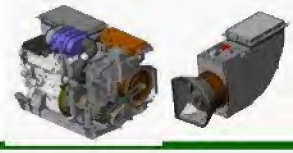


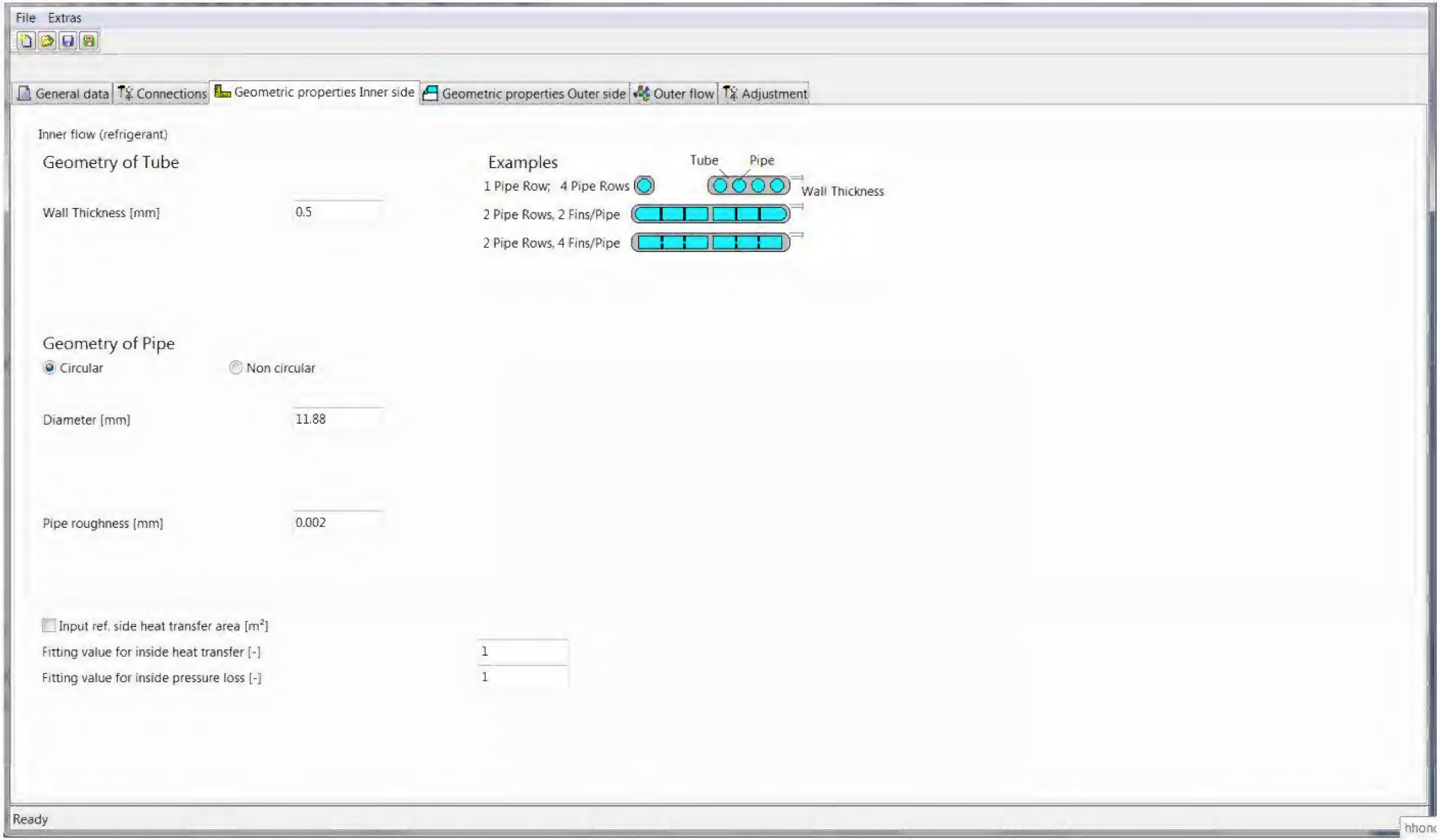


XV_Snake_Drive_Condenser_TKPIT.kuliCnd

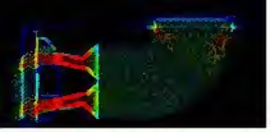


1.Condensor: Component parameters

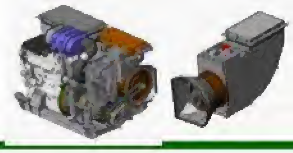


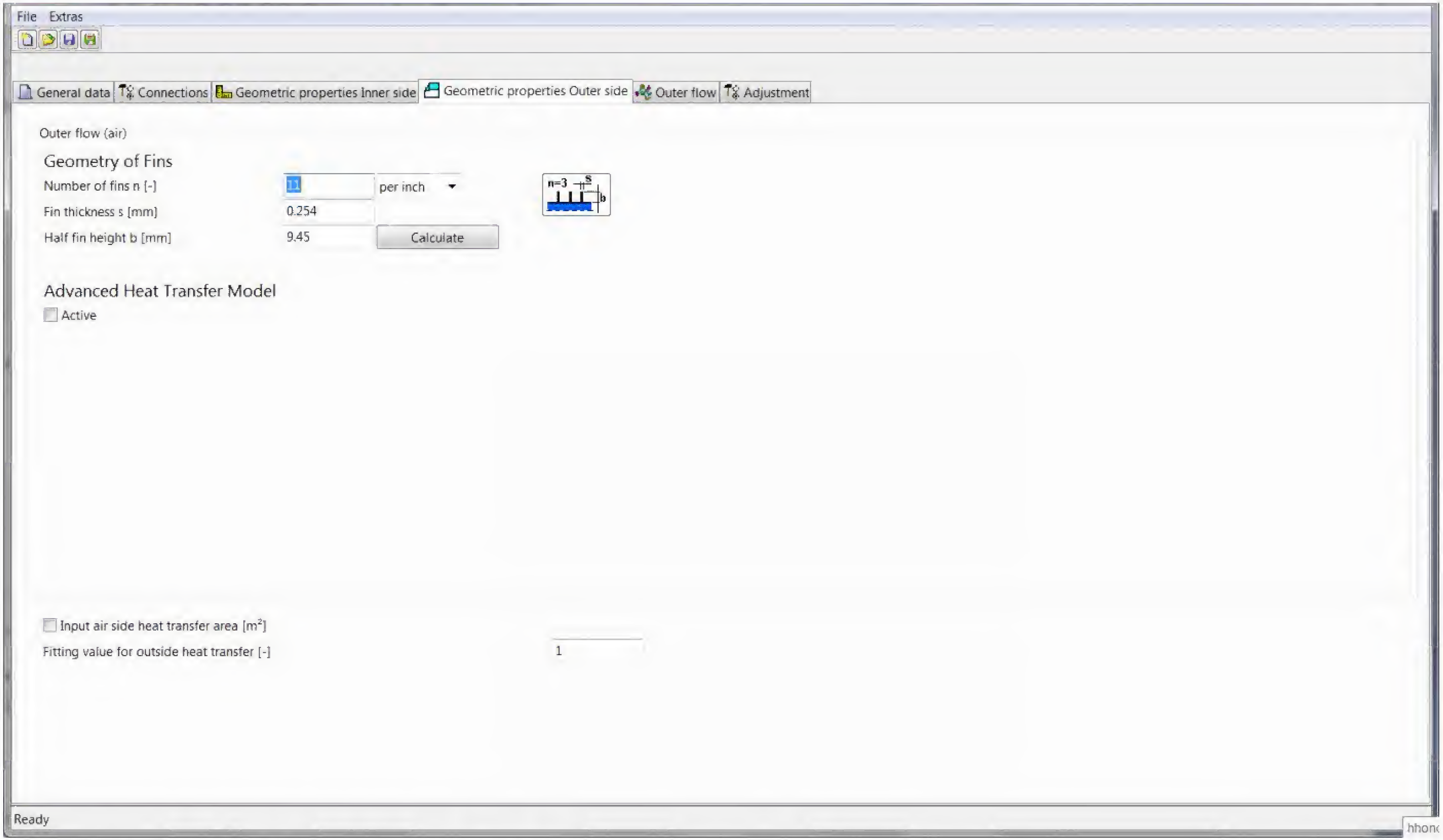


XV_Snake_Drive_Condenser_TKPIT.kuliCnd



1.Condensor: Component parameters





XV_Snake_Drive_Condenser_TKPIT.kuliCnd

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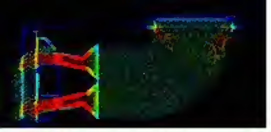
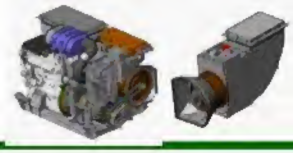


1.Condensor: Component parameters



File Extras

General data | Connections | Geometric properties Inner side | Geometric properties Outer side | Outer flow | Adjustment

(•) Defined by characteristic curve(s)
( ) Defined by parameters

Entry pressure abs. [hPa]: 1013

Medium: Air
Air humidity [%]: 0
Ref. temp. (rel. humidity) [°C]: 20
Ref. press. (rel. humidity) [hPa]: 1013

Reference area width [mm]: 319
Reference area height [mm]: 457
Depth [mm]: 83

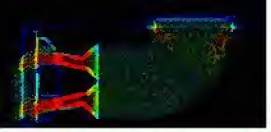
Regression: no regression

[1]

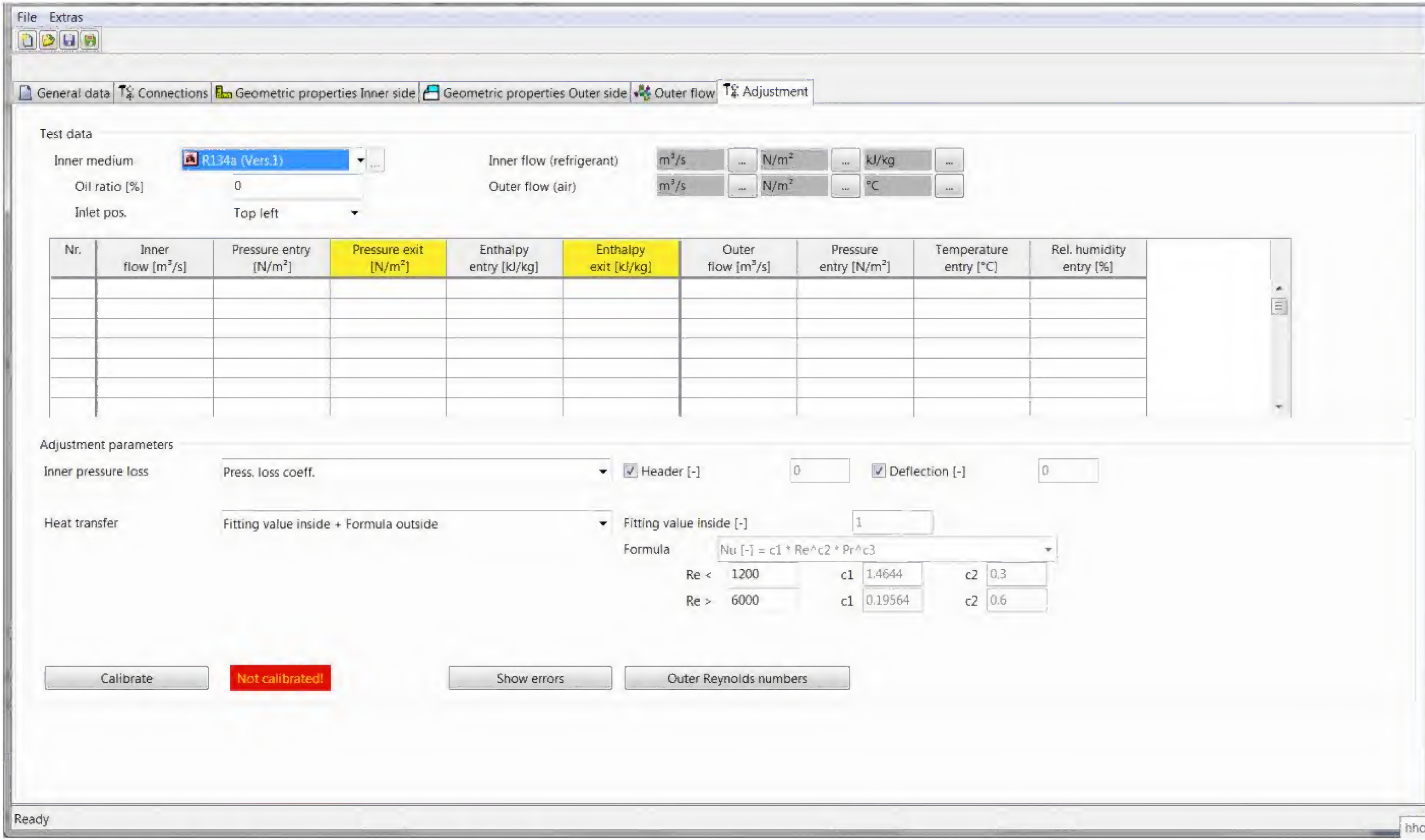
Flowrate [ft³/min]...	Pressure loss [inH2O]...	Entry temp [°C]...
500	0.0899325	45
1000	0.318928	45
2000	1.13208	45
3000	2.36656	45
4000	3.97912	45
5000	5.94118	45
7000	11.2626	45
9000	17.5779	45
12000	29.711	45

Ready

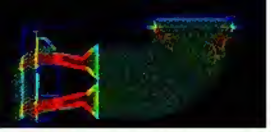
XV_Snake_Drive_Condenser_TKPIT.kuliCnd



1.Condensor: Component parameters



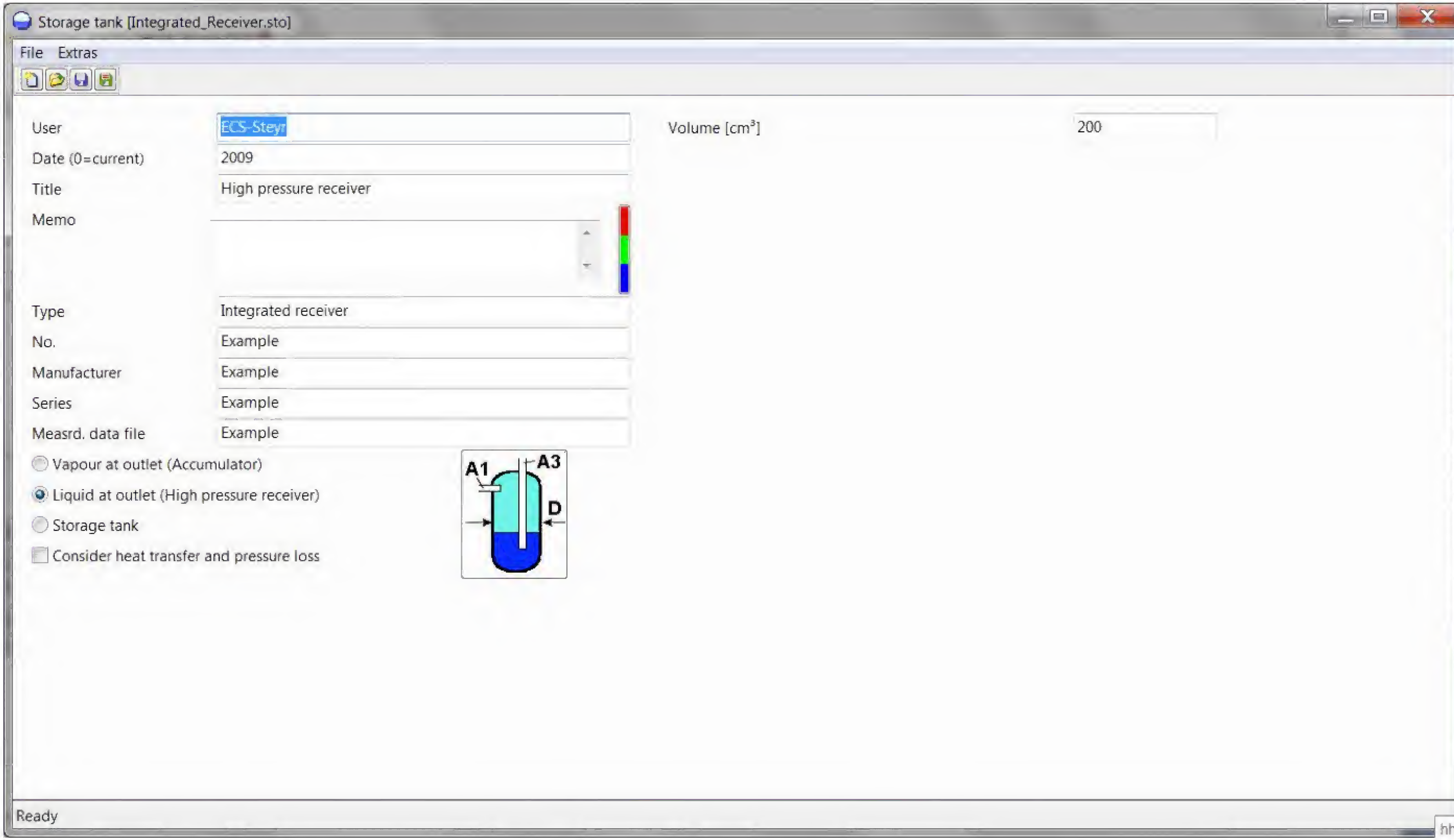
XV_Snake_Drive_Condenser_TKPIT.kuliCnd



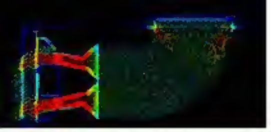
1.Storage Tank: Component parameters

Integrated_Receiver.sto

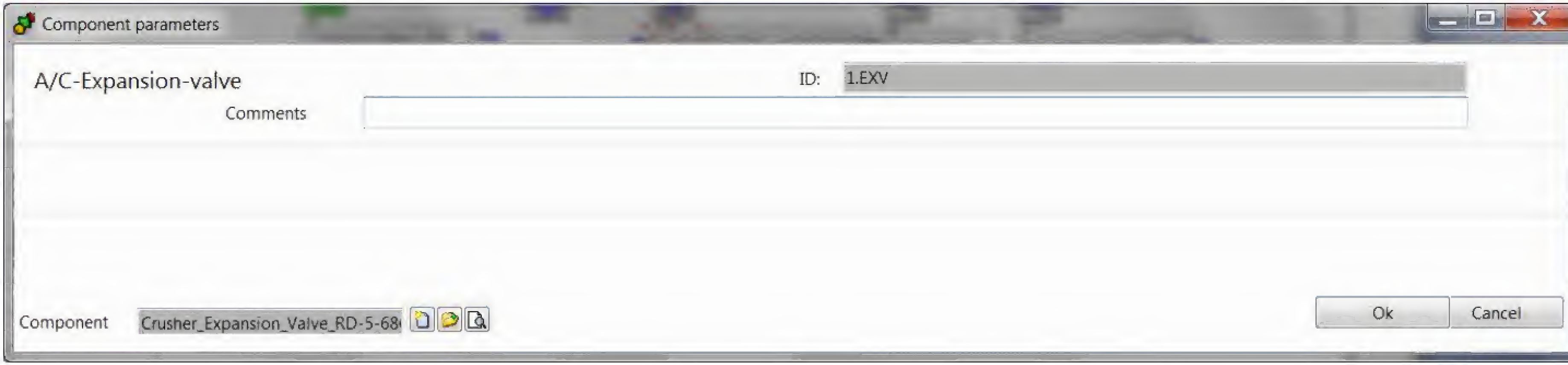
1.Storage Tank: Component parameters



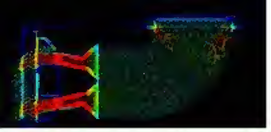
Integrated_Receiver.sto



1.A/C-Expansion-Valve: Component parameters

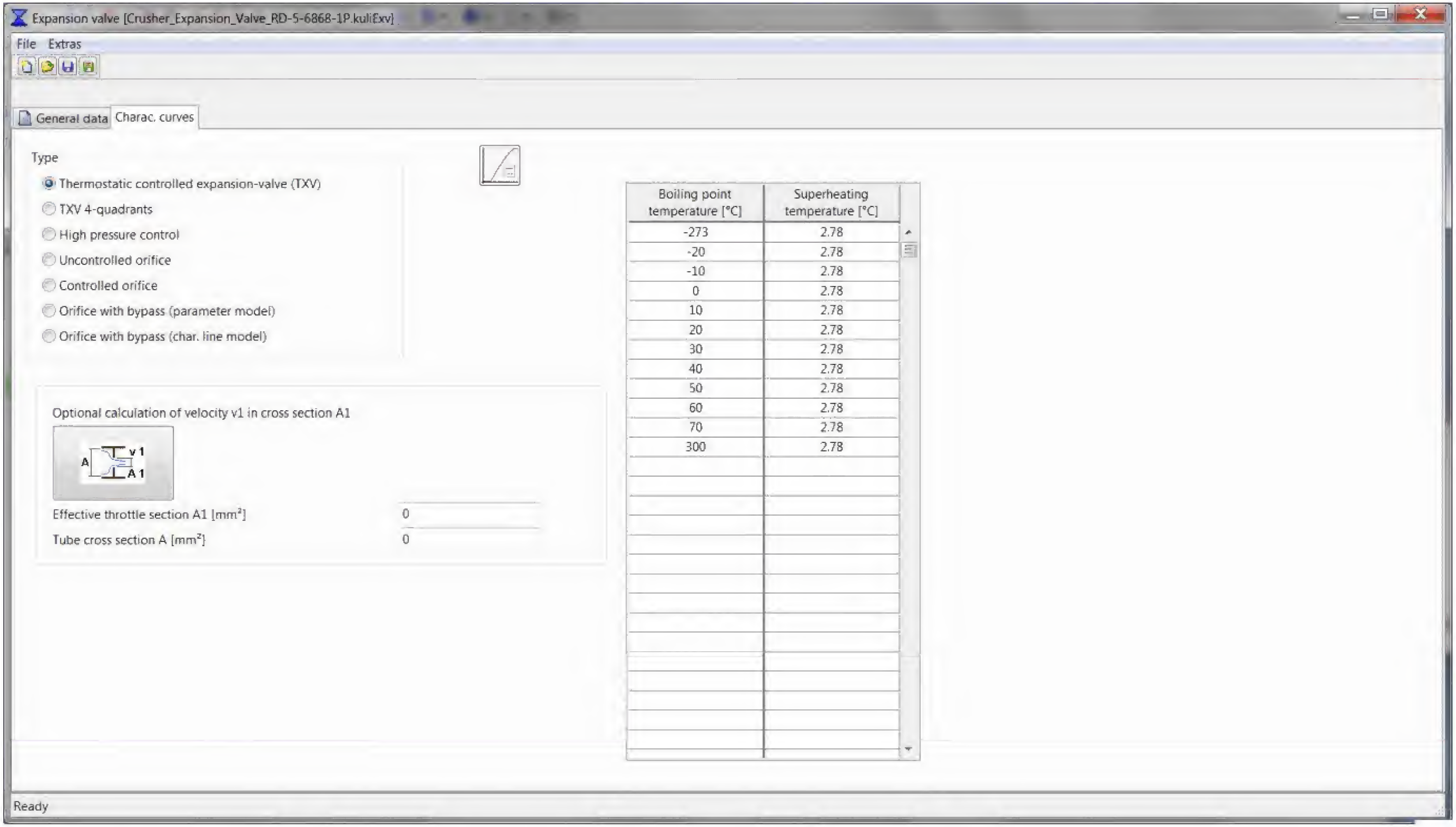


Crusher_Expansion_Valve_RD-5-6868-1P.kuliExv



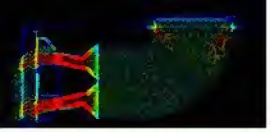
1.A/C-Expansion-Valve: Component parameters

Type: RD-5-6868-1P

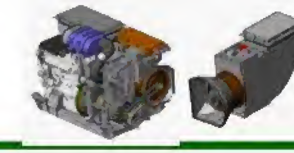


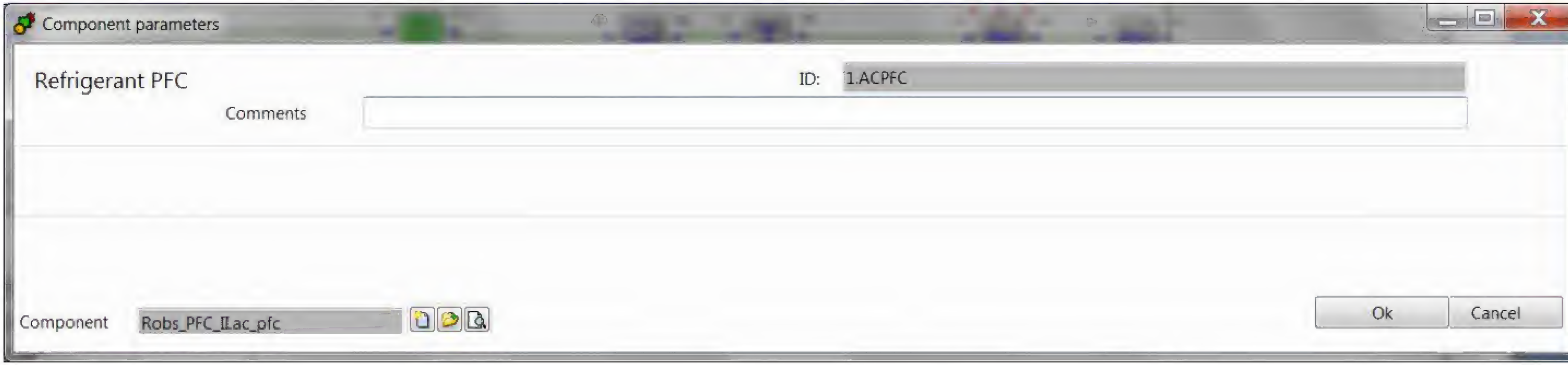
Boiling point temperature [°C]	Superheating temperature [°C]
-273	2.78
-20	2.78
-10	2.78
0	2.78
10	2.78
20	2.78
30	2.78
40	2.78
50	2.78
60	2.78
70	2.78
300	2.78

Crusher_Expansion_Valve_RD-5-6868-1P.kuliExv

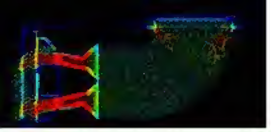


1. Refrigerant PFC: Component parameters

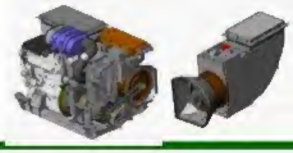


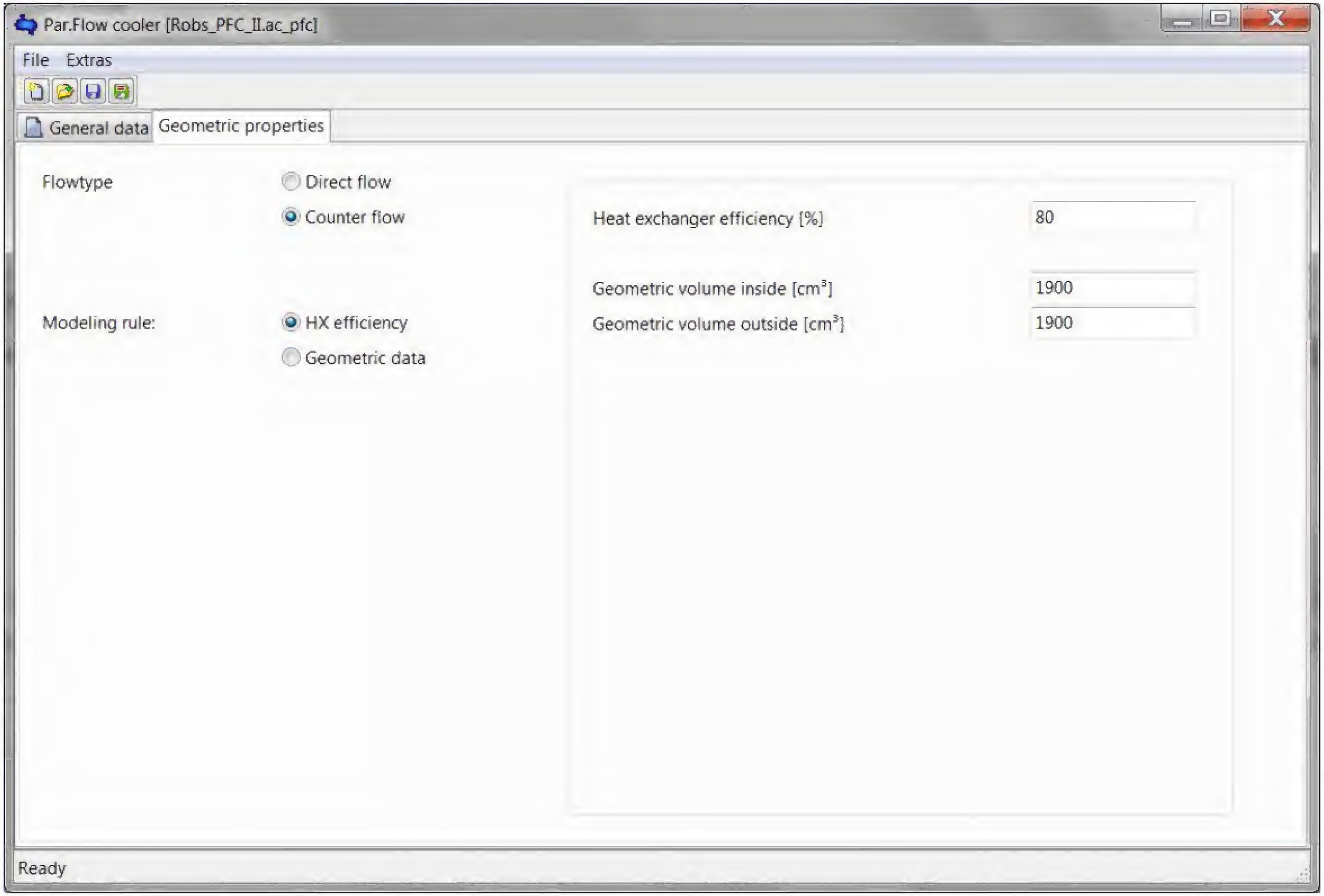


Robs_PFC_II.ac_pfc

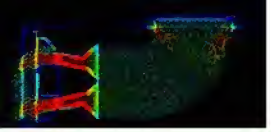


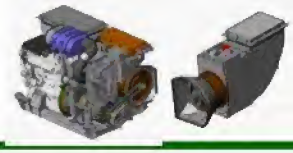
1. Refrigerant PFC: Component parameters





Robs_PFC_II.ac_pfc

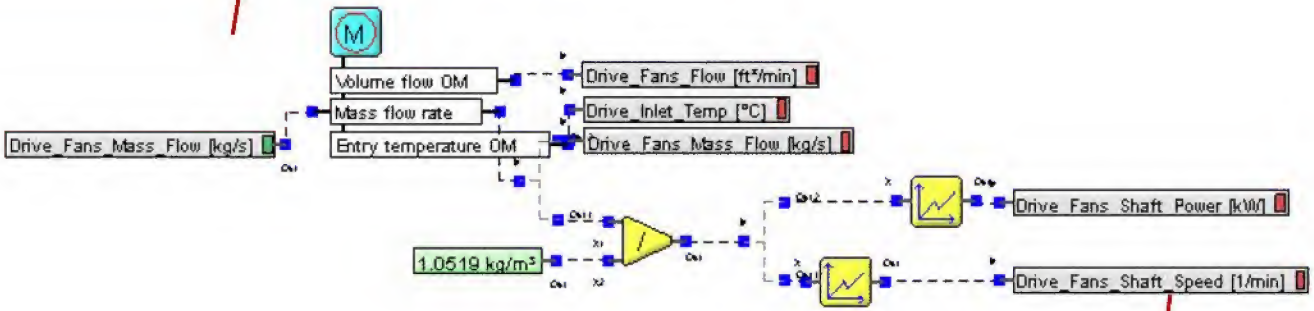




Drive Snake Air Flow

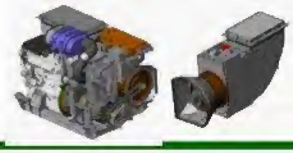
- **Input mass flow rate from Simulink**

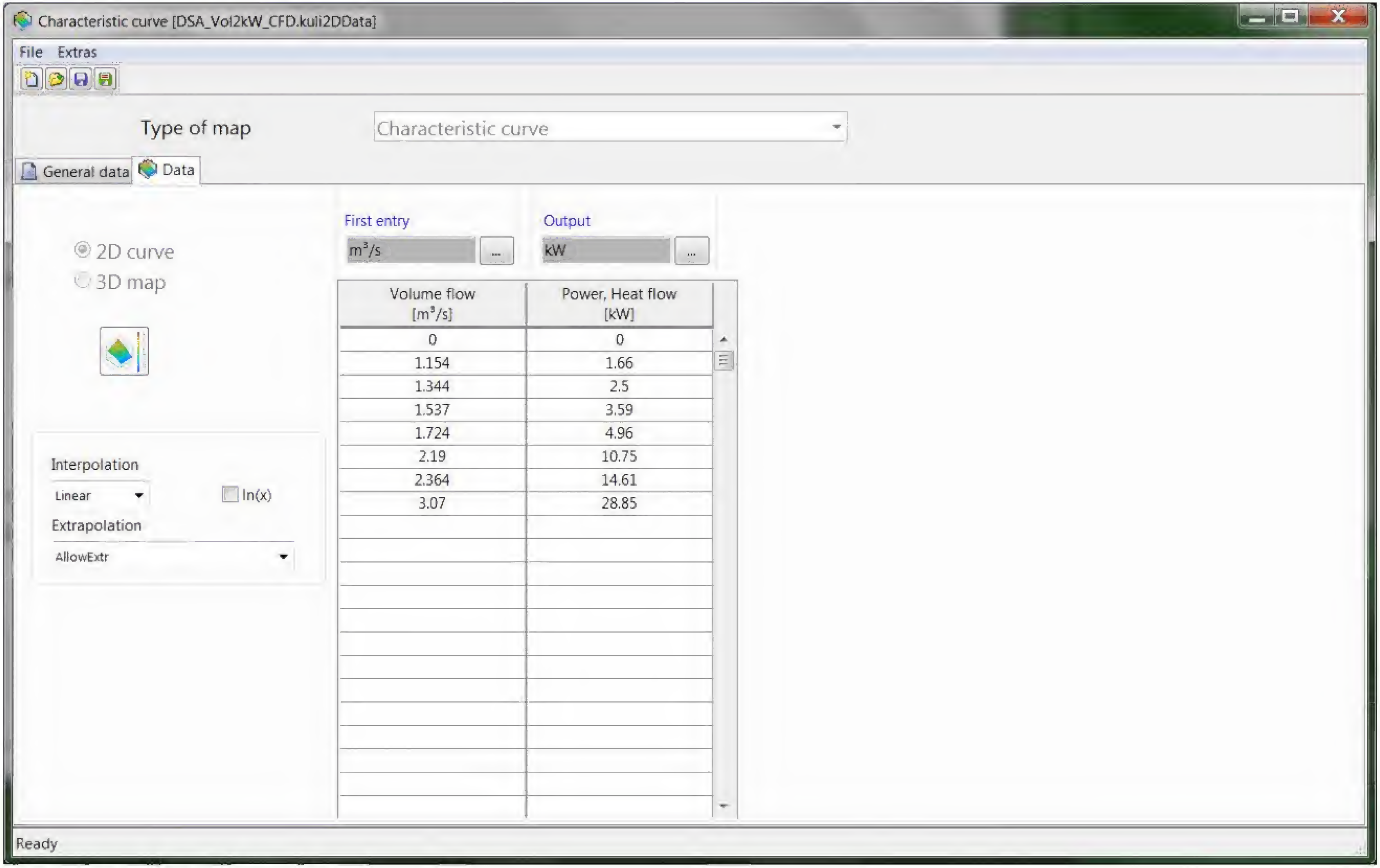
Air flow rate through Engine Snake Heat Exchangers – The input "Drive_Fans_Mass_Flow [kg/s]" represents the mass flow rate of the air at specific fan speeds. This is one of the overall control parameters



Fan Speed and Power

Kuli Drive Snake Air Flow - Output

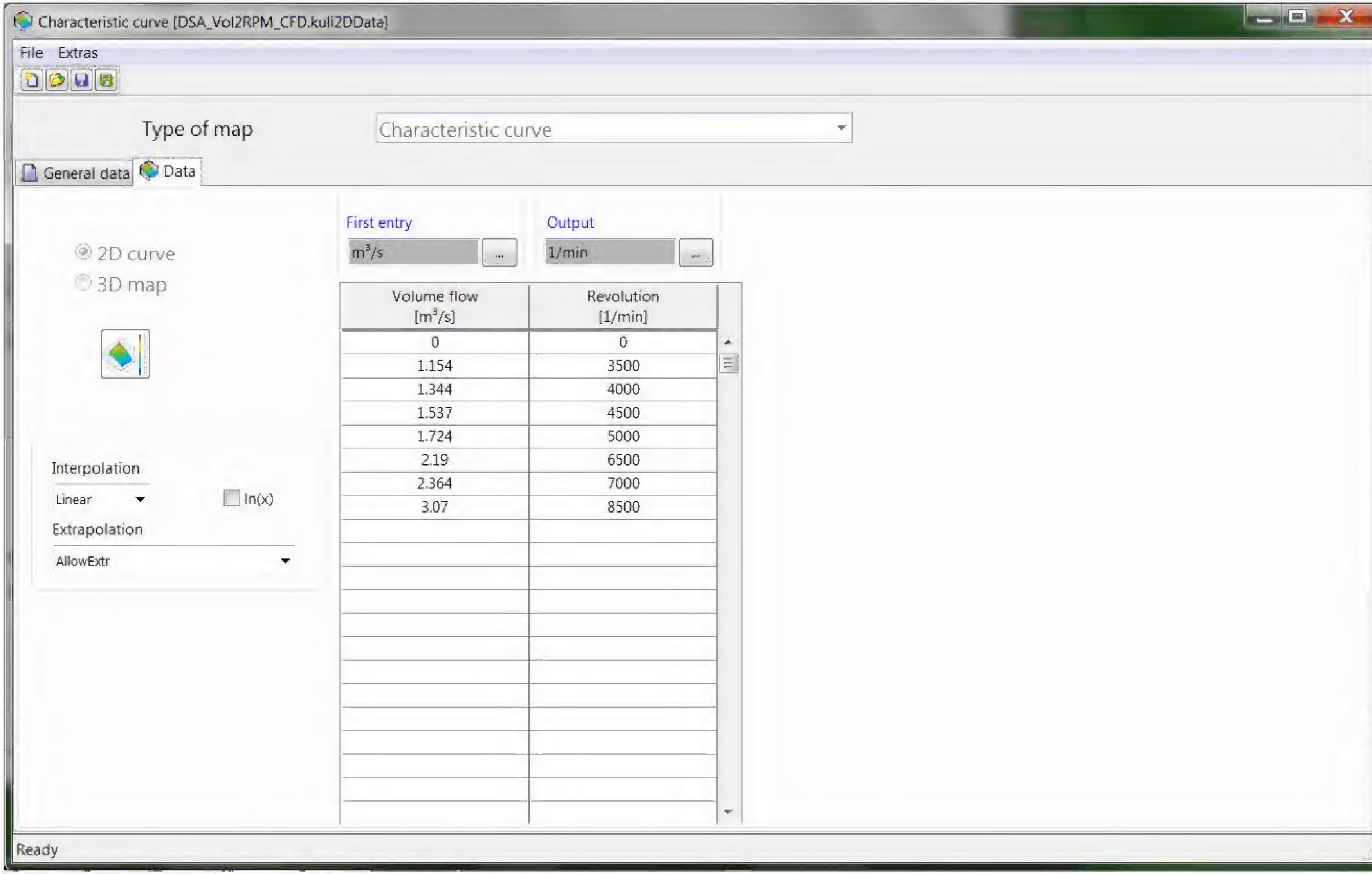




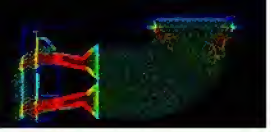
Volume flow [m³/s]	Power, Heat flow [kW]
0	0
1.154	1.66
1.344	2.5
1.537	3.59
1.724	4.96
2.19	10.75
2.364	14.61
3.07	28.85

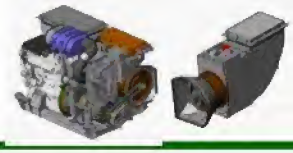
DSA_Vol2kW_CFD.kuli2DData

Kuli Drive Snake Air Flow - Output



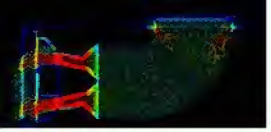
DSA_Vol2RPM_CFD.kuli2DData

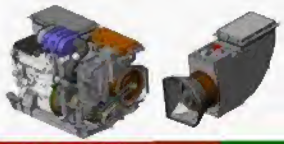


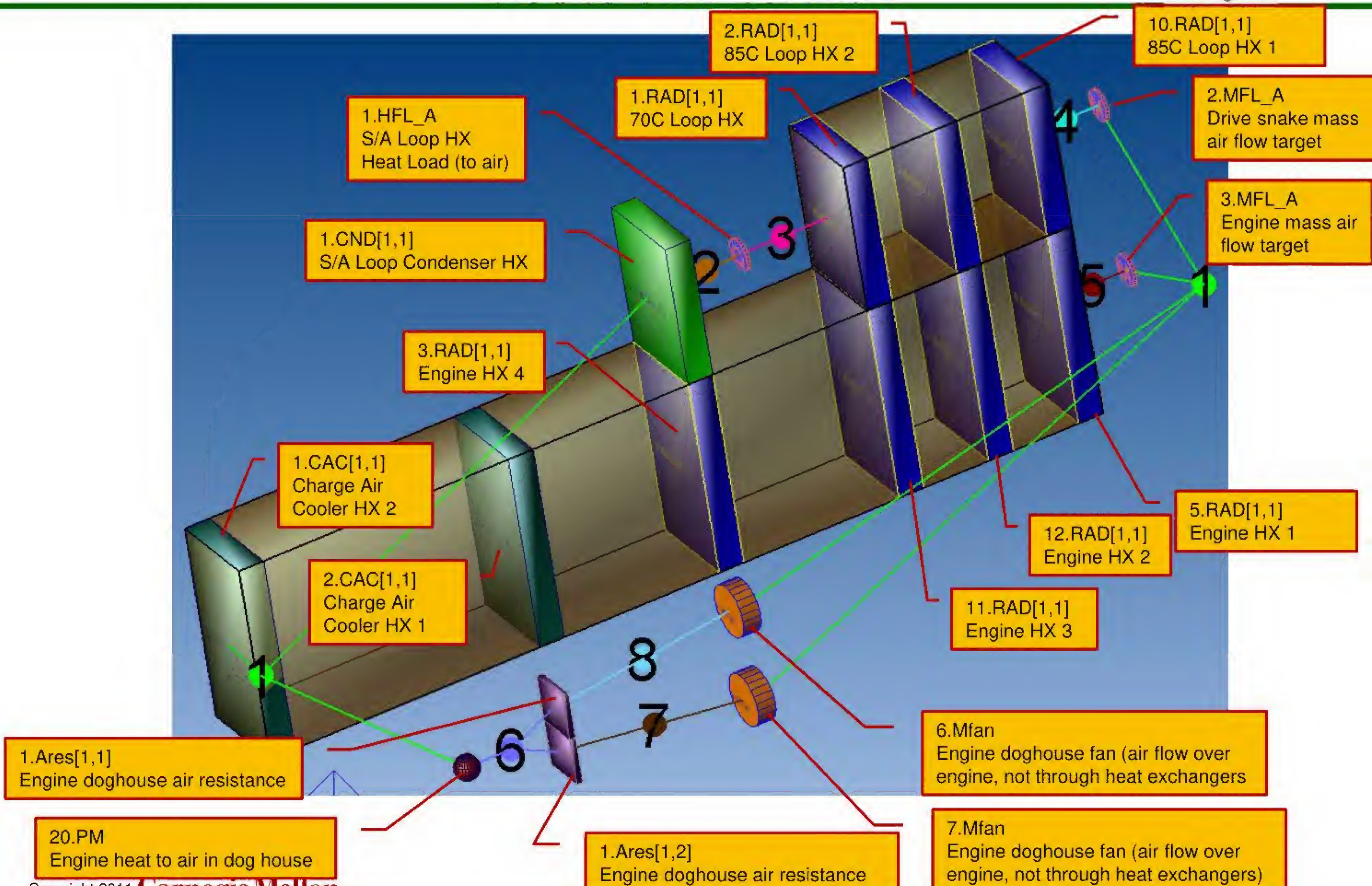


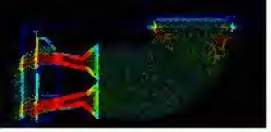
Air side – Heat Exchanger Order

XV KULI Model – 3D Air Path Details

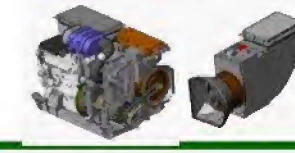






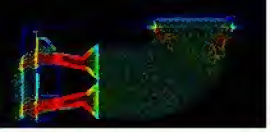


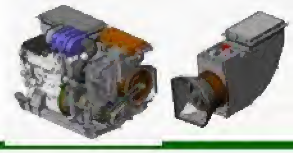
XV KULI Model Overview – Air side components



Air side components - locations and functions

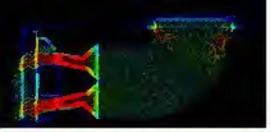
ID	Width Diameter	Height [mm]	Depth [mm]	Pos x [mm]	Pos y [mm]	Pos z [mm]	Comments
- Components							
1.Area resistance	150	300	20	200	-375	0	Backpressure inside engine compartment
1.Condenser	319	457	83	500	375	635	SA HVAC Condenser
2.Charge air cooler	319	635	83	0	375	0	CAC 2 Radiator
3.Charge air cooler	319	635	83	250	375	0	CAC 1 Radiator
6.Mechanically driven fan	167	167	59	300	-300	0	Fan pulls ambient air into and through the engine compartment
7.Mechanically driven fan	167	167	59	300	-300	300	Fan pulls ambient air into and through the engine compartment
20.Point Mass	-	-	-	100	-300	150	Engine heat (other than exhaust or coolant) convecting to air in the engine compartment
2.Mass flow target (Air)	-	-	-	1500	535	877	Drive snake air flow (represents mass flow rate pulled through drive snake by the fan)
3.Mass flow target (Air)	-	-	-	1500	535	318	Engine snake air flow (represents mass flow rate pulled through drive snake by the fan)
1.Heat flow source (Air)	-	-	-	600	535	877	SA HVAC loop heat to air - flows into 70C radiator
1.Radiator	319	483	83	750	375	635	70C Loop Radiator
10.Radiator	319	483	83	1250	375	635	85C Loop Radiator 1
11.Radiator	319	635	83	750	375	0	Engine Radiator 2
12.Radiator	319	635	83	1000	375	0	Engine radiator 3
2.Radiator	319	483	83	1000	375	635	85C Loop Radiator 2
3.Radiator	319	635	83	500	375	0	Engine radiator 4
5.Radiator	319	635	83	1250	375	0	Engine Radiator 1

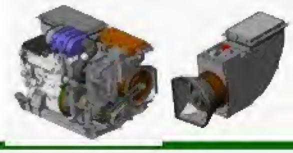




Common Components –

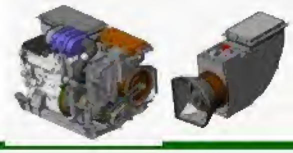
Used in more than one loop

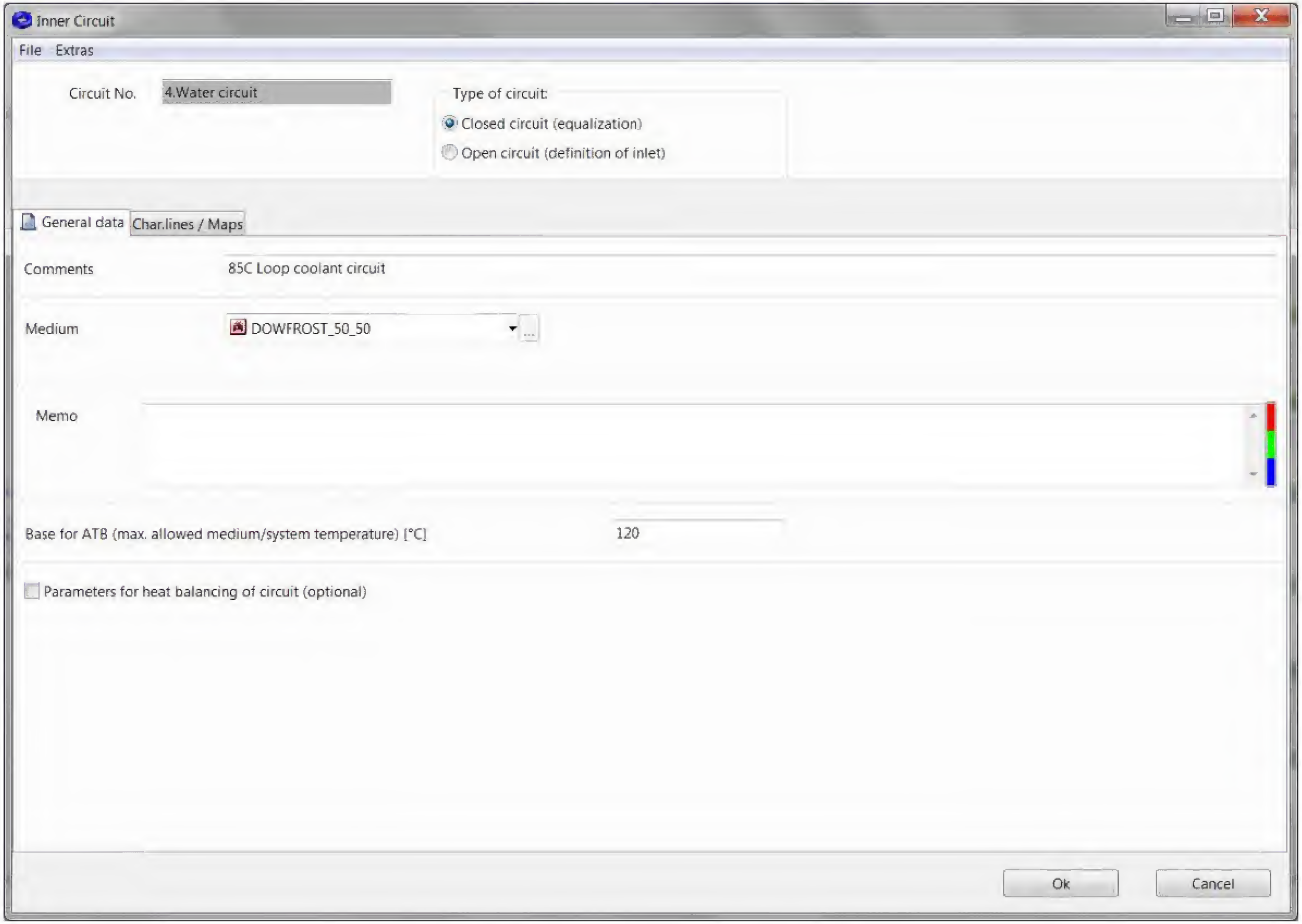




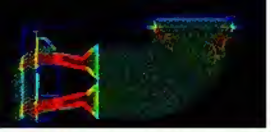
Working Fluids

EGW – 50/50

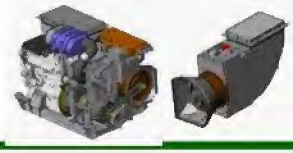


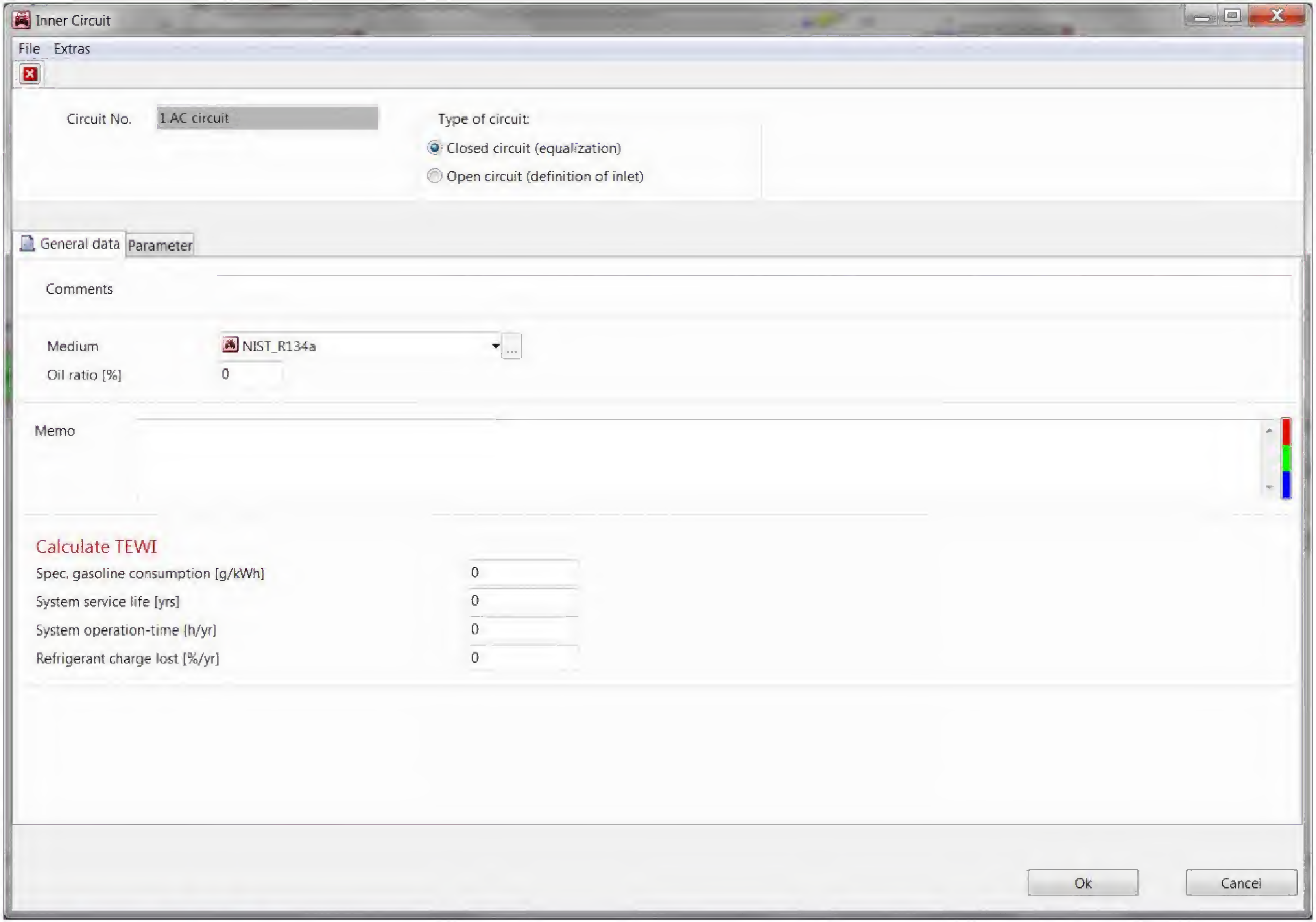


Inner Circuit
File
Extras
Circuit No.
4.Water circuit
Type of circuit:
Closed circuit (equalization)
Open circuit (definition of inlet)
General data
Char.lines / Maps
Comments
85C Loop coolant circuit
Medium
DOWFROST_50_50
Memo
Base for ATB (max. allowed medium/system temperature) [°C]
120
Parameters for heat balancing of circuit (optional)
Ok
Cancel

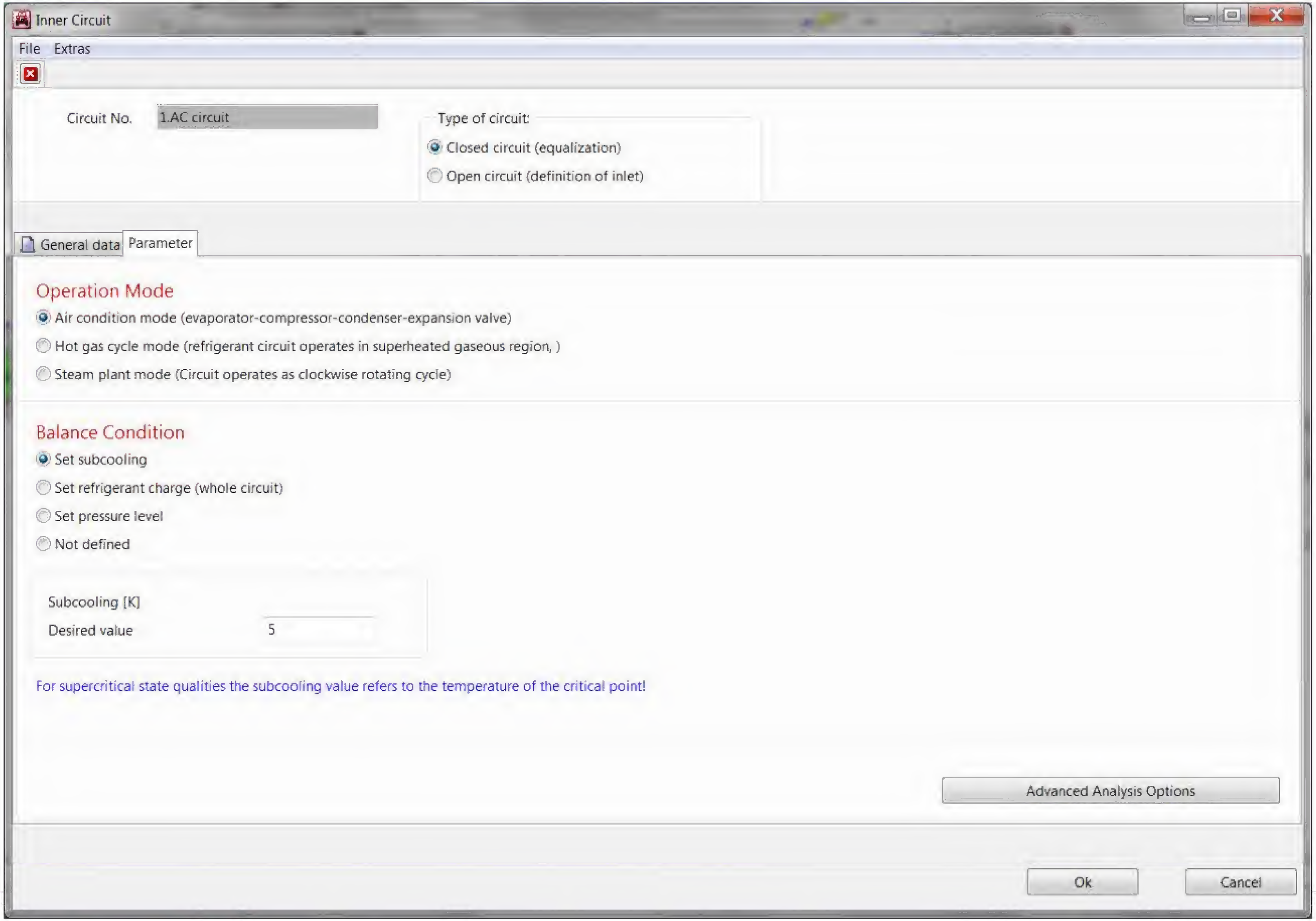


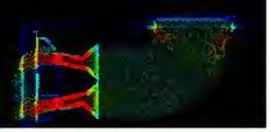
R134a Parameters

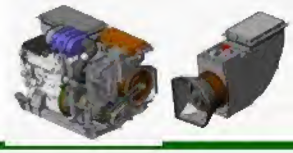




R134a Parameters

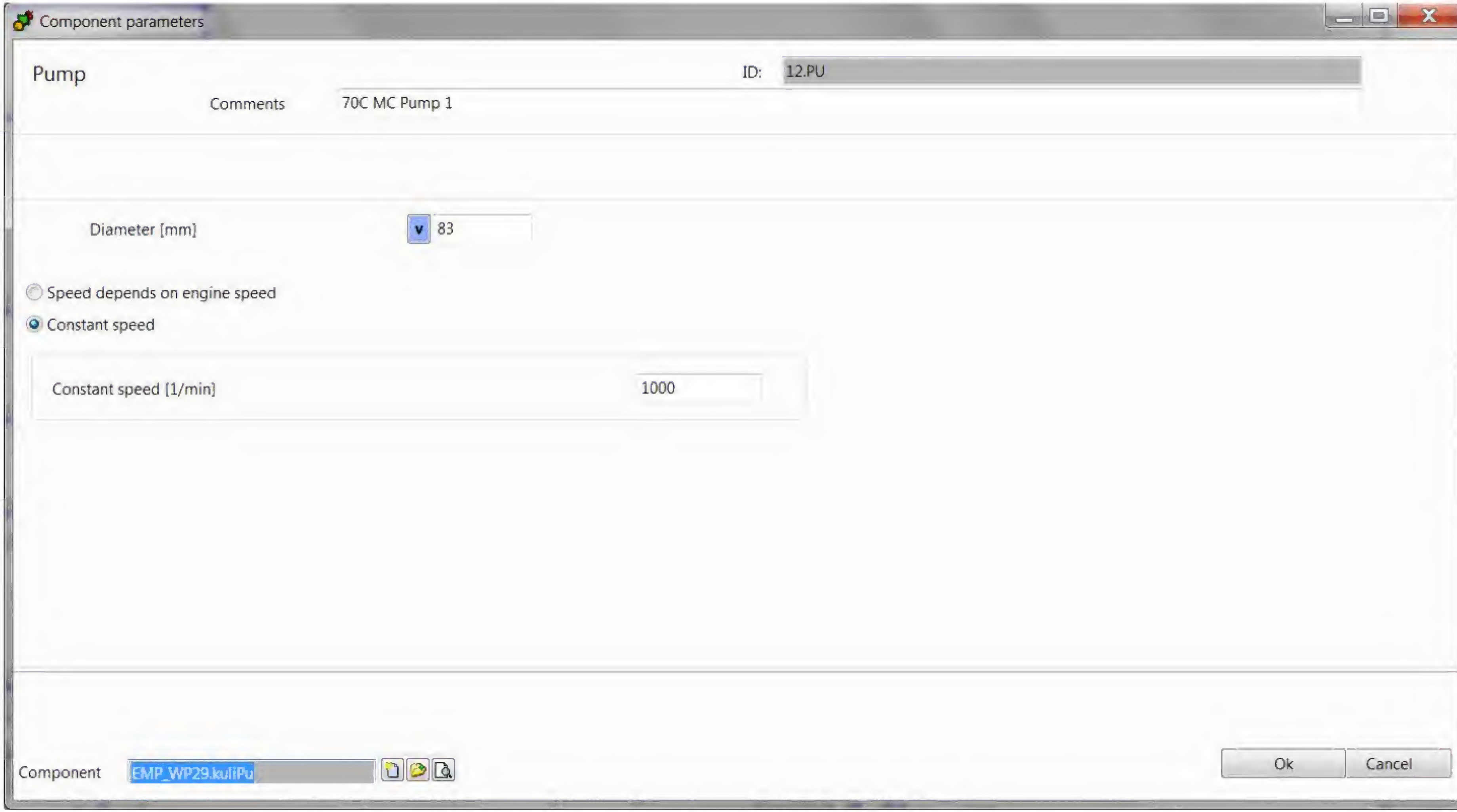






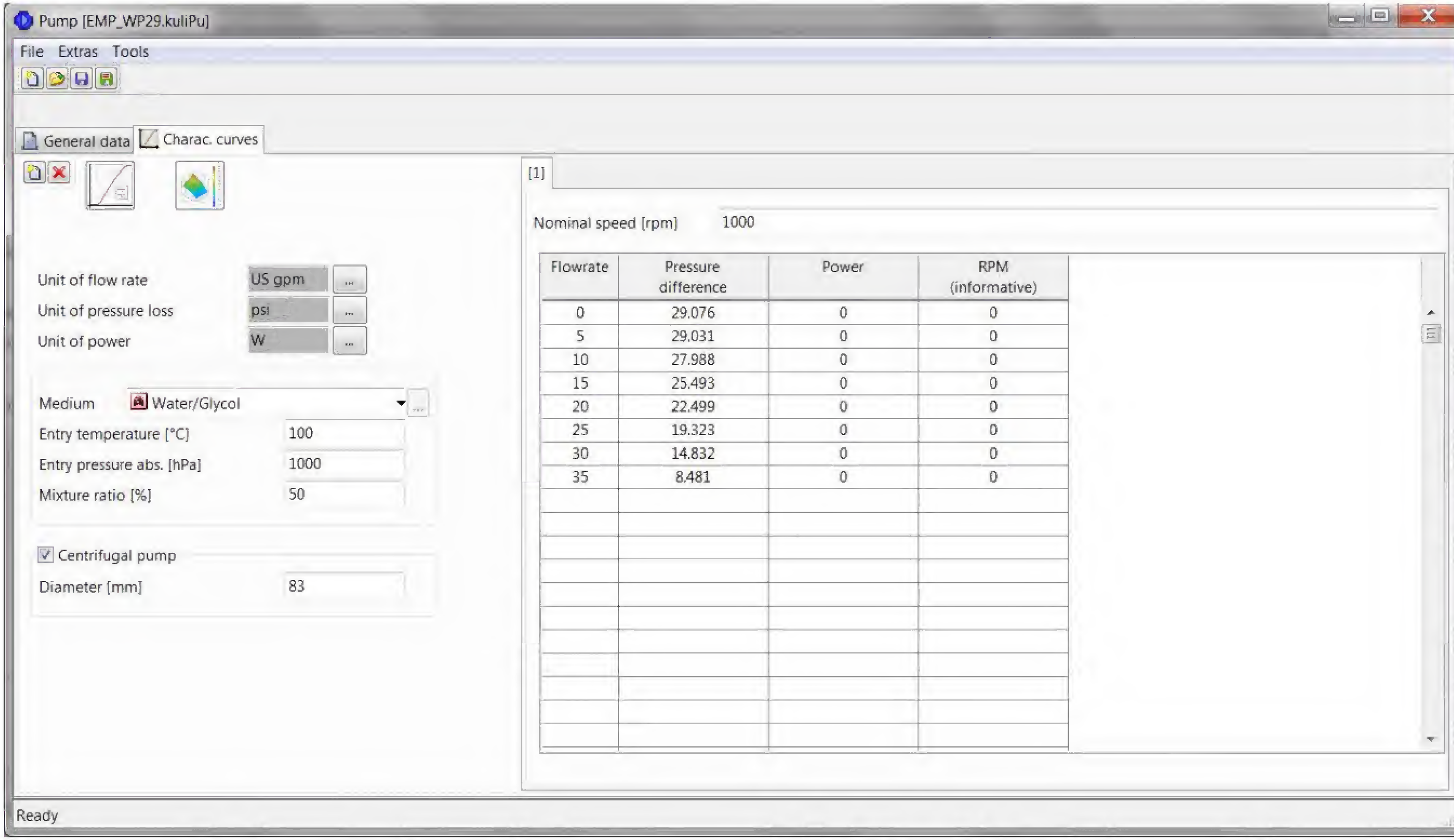
Pump

Electric Pump

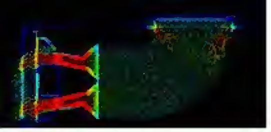


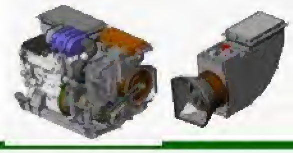
EMP_WP29.kuliPu

Electric Pump



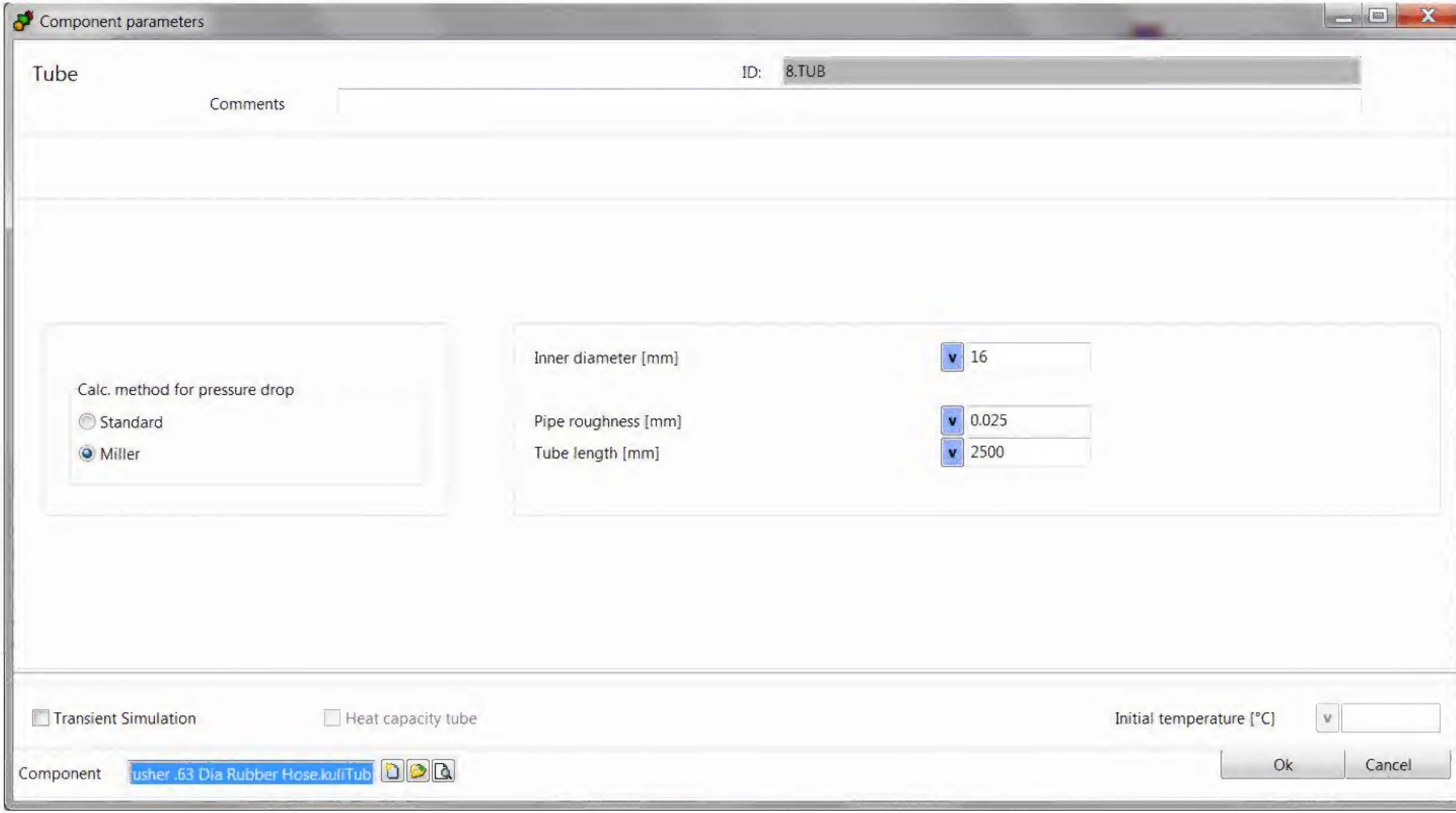
EMP_WP29.kuliPu



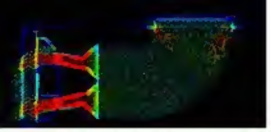


Hoses, Tubes, Fittings

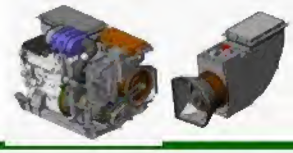
0.63" Rubber Hose

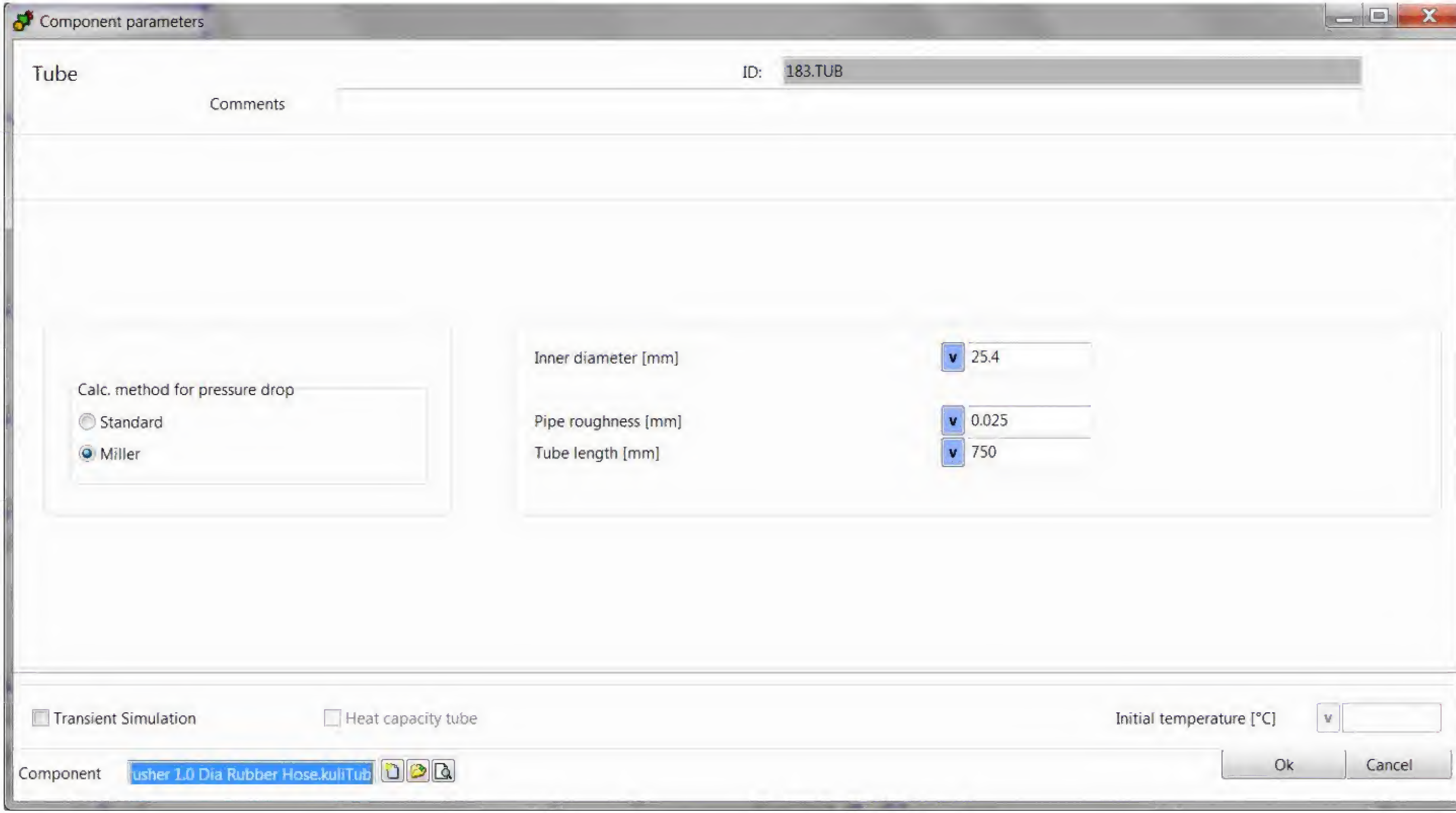


Crusher .63 Dia Rubber Hose.kuliTub



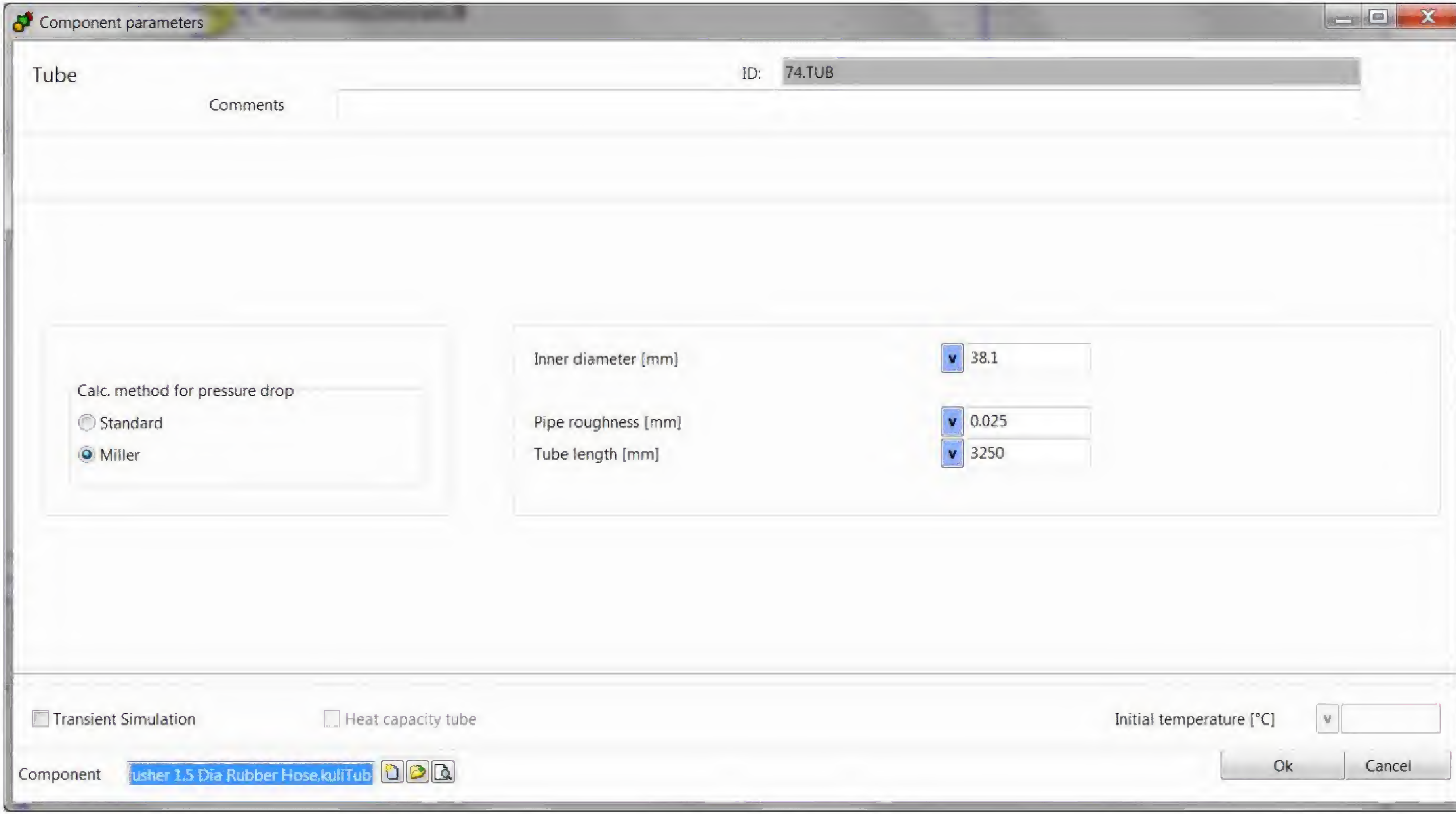
1" dia rubber hose





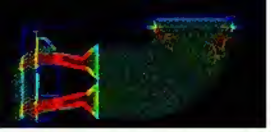
Crusher 1.0 Dia Rubber Hose.kuliTub

1.5” dia rubber hose

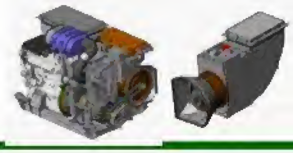


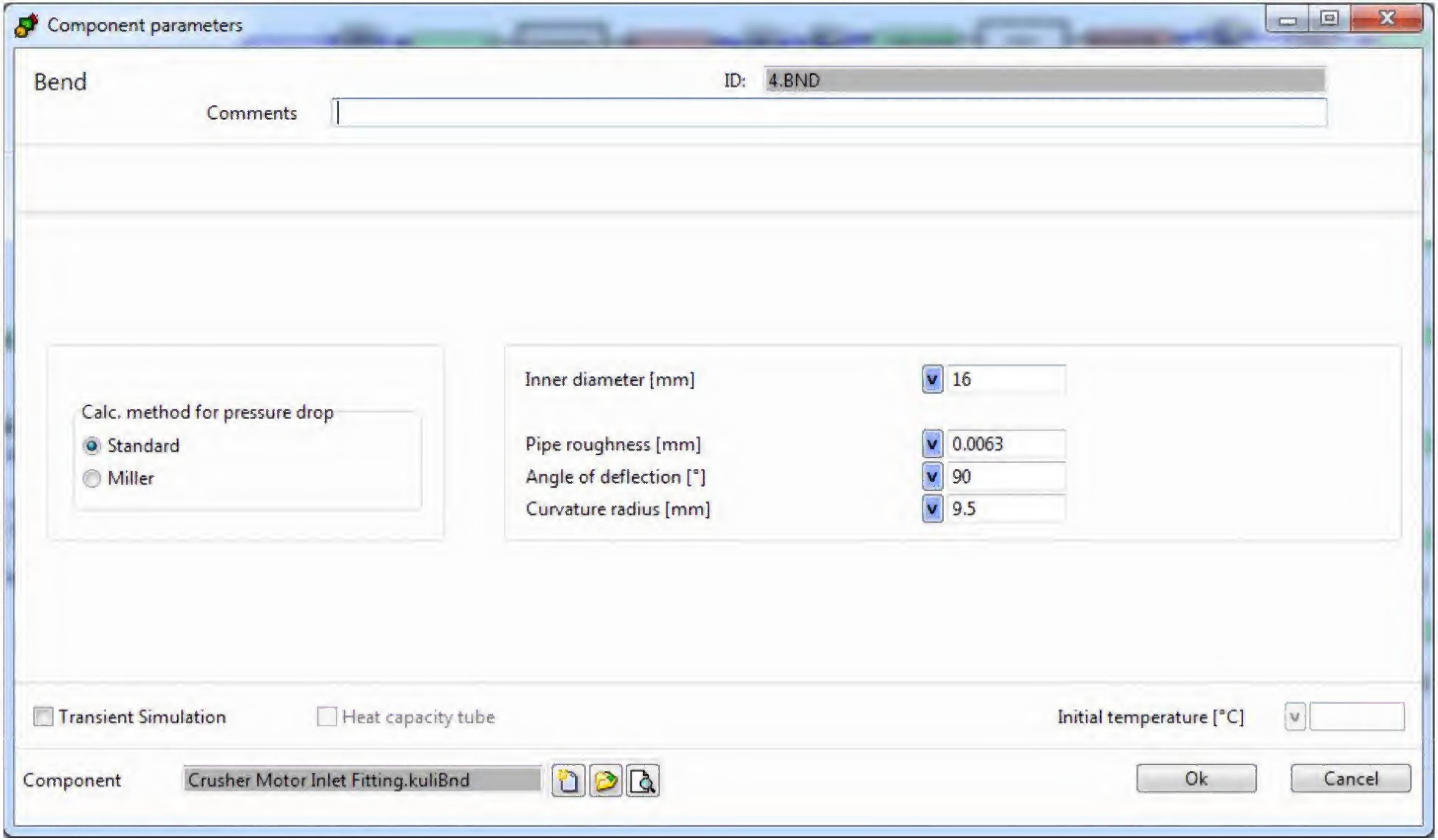
Crusher 1.5 Dia Rubber Hose.kuliTub

See 182.Tube for component file information and available COM I/O.

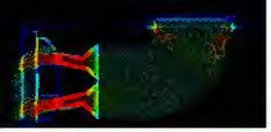


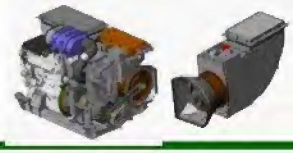
Motor 90° Fitting



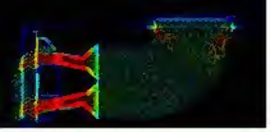


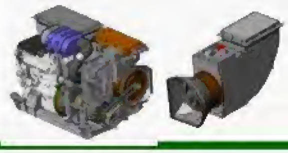
Crusher .63 Dia Rubber Hose.kuliTub





Heat Exchangers

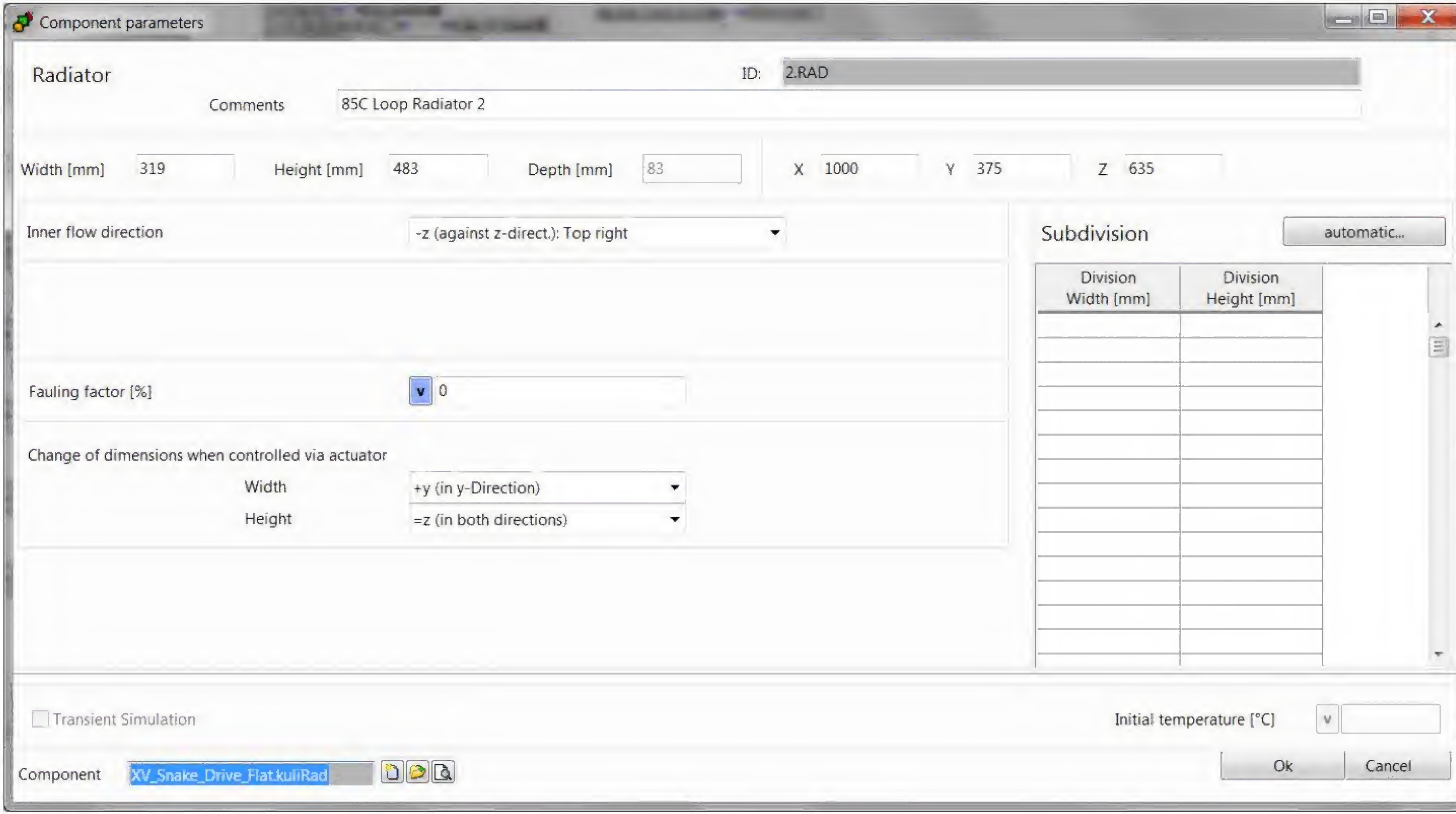




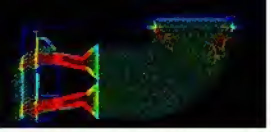
EGW Radiator Parameters

– Engine, 85C, 70C

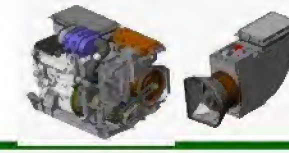
EGW Radiator Parameters – Engine, 85C, 70C

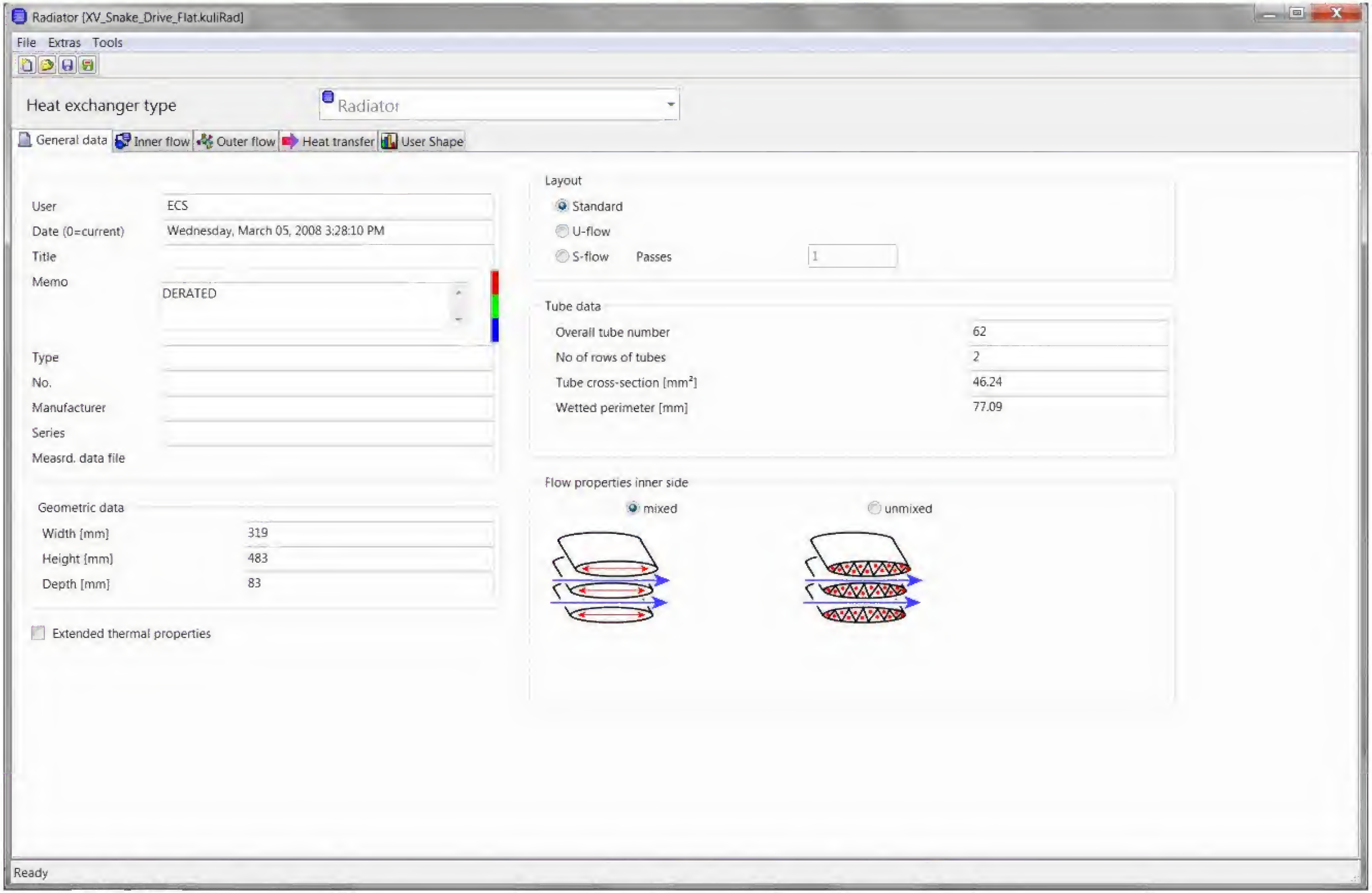


XV_Snake_Drive_Flat.kuliRad

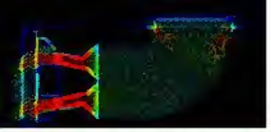


EGW Radiator Parameters – Engine, 85C, 70C

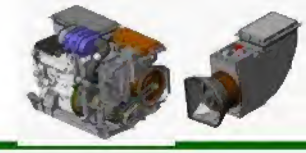


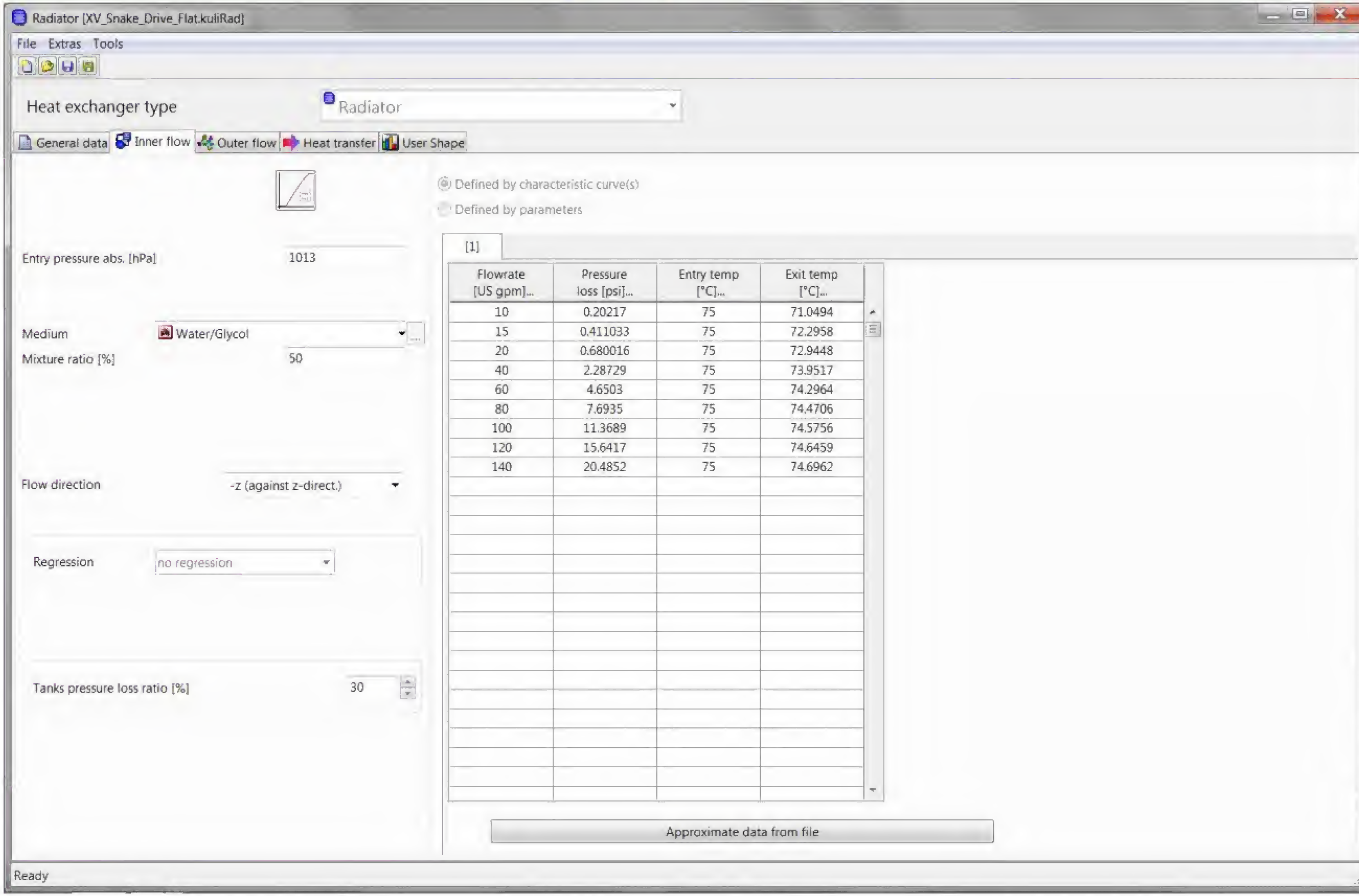


XV_Snake_Drive_Flat.kuliRad



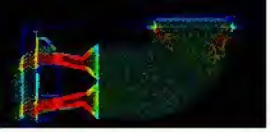
EGW Radiator Parameters – Engine, 85C, 70C



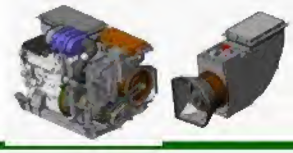


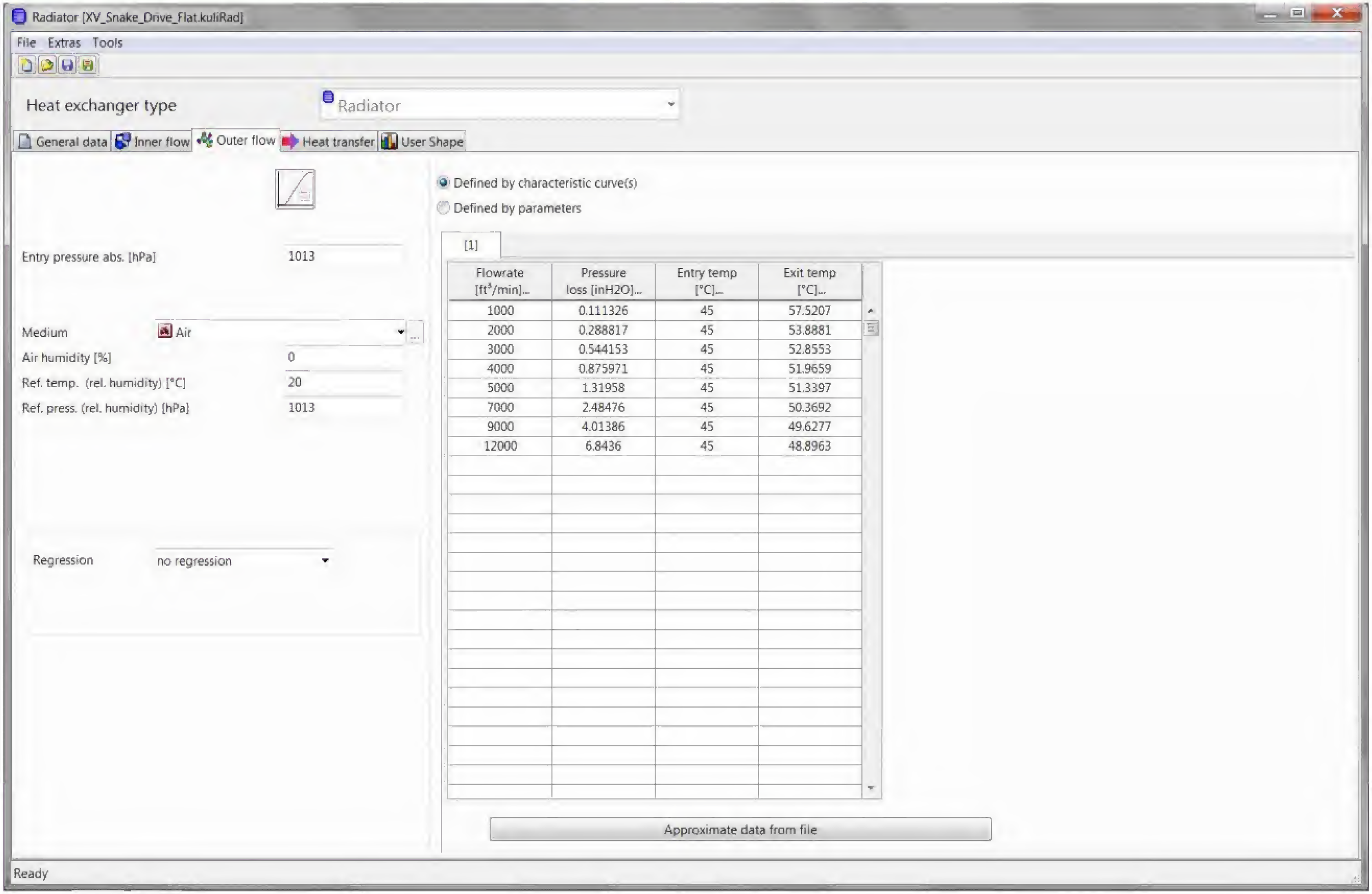
Flowrate [US gpm]...	Pressure loss [psi]...	Entry temp [°C]...	Exit temp [°C]...
10	0.20217	75	71.0494
15	0.411033	75	72.2958
20	0.680016	75	72.9448
40	2.28729	75	73.9517
60	4.6503	75	74.2964
80	7.6935	75	74.4706
100	11.3689	75	74.5756
120	15.6417	75	74.6459
140	20.4852	75	74.6962

XV_Snake_Drive_Flat.kuliRad



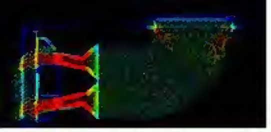
EGW Radiator Parameters – Engine, 85C, 70C



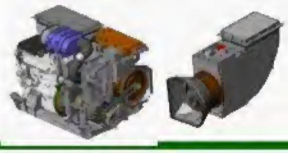


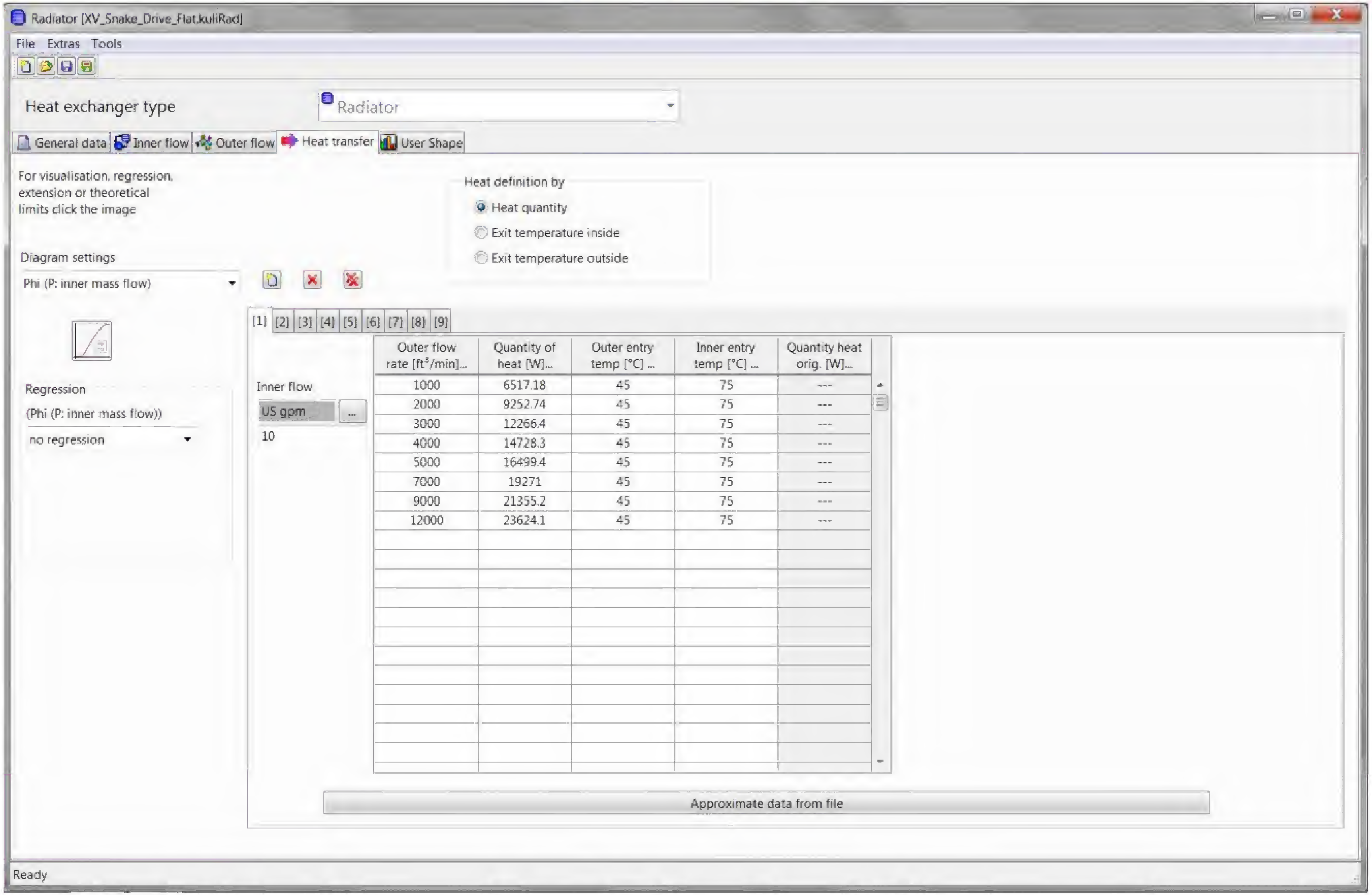
Flowrate [ft³/min]...	Pressure loss [inH2O]...	Entry temp [°C]...	Exit temp [°C]...
1000	0.111326	45	57.5207
2000	0.288817	45	53.8881
3000	0.544153	45	52.8553
4000	0.875971	45	51.9659
5000	1.31958	45	51.3397
7000	2.48476	45	50.3692
9000	4.01386	45	49.6277
12000	6.8436	45	48.8963

XV_Snake_Drive_Flat.kuliRad



EGW Radiator Parameters – Engine, 85C, 70C



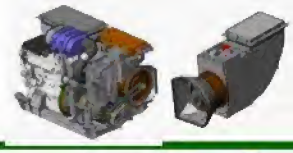


Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	6517.18	45	75	---
2000	9252.74	45	75	---
3000	12266.4	45	75	---
4000	14728.3	45	75	---
5000	16499.4	45	75	---
7000	19271	45	75	---
9000	21355.2	45	75	---
12000	23624.1	45	75	---

XV_Snake_Drive_Flat.kuliRad

NATIONAL ROBOTICS NREC ENGINEERING CENTER

EGW Radiator Parameters – Engine, 85C, 70C



Radiator [XV_Snake_Drive_Flat.kuliRad]

File Extras Tools

Heat exchanger type: Radiator

General data | Inner flow | Outer flow | Heat transfer | User Shape

For visualisation, regression, extension or theoretical limits click the image

Heat definition by
- (•) Heat quantity
- ( ) Exit temperature inside
- ( ) Exit temperature outside

Diagram settings: Phi (P: inner mass flow)

[1] [2] [3] [4] [5] [6] [7] [8] [9]

Theor. limits

Inner flow: US gpm 15

Regression (Phi (P: inner mass flow)): no regression

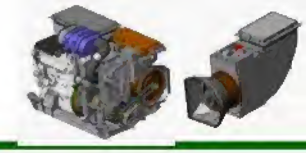
Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	6639.28	45	75	---
2000	9500.29	45	75	---
3000	12744	45	75	---
4000	15405	45	75	---
5000	17480.7	45	75	---
7000	20752.6	45	75	---
9000	23018	45	75	---
12000	25705.3	45	75	---

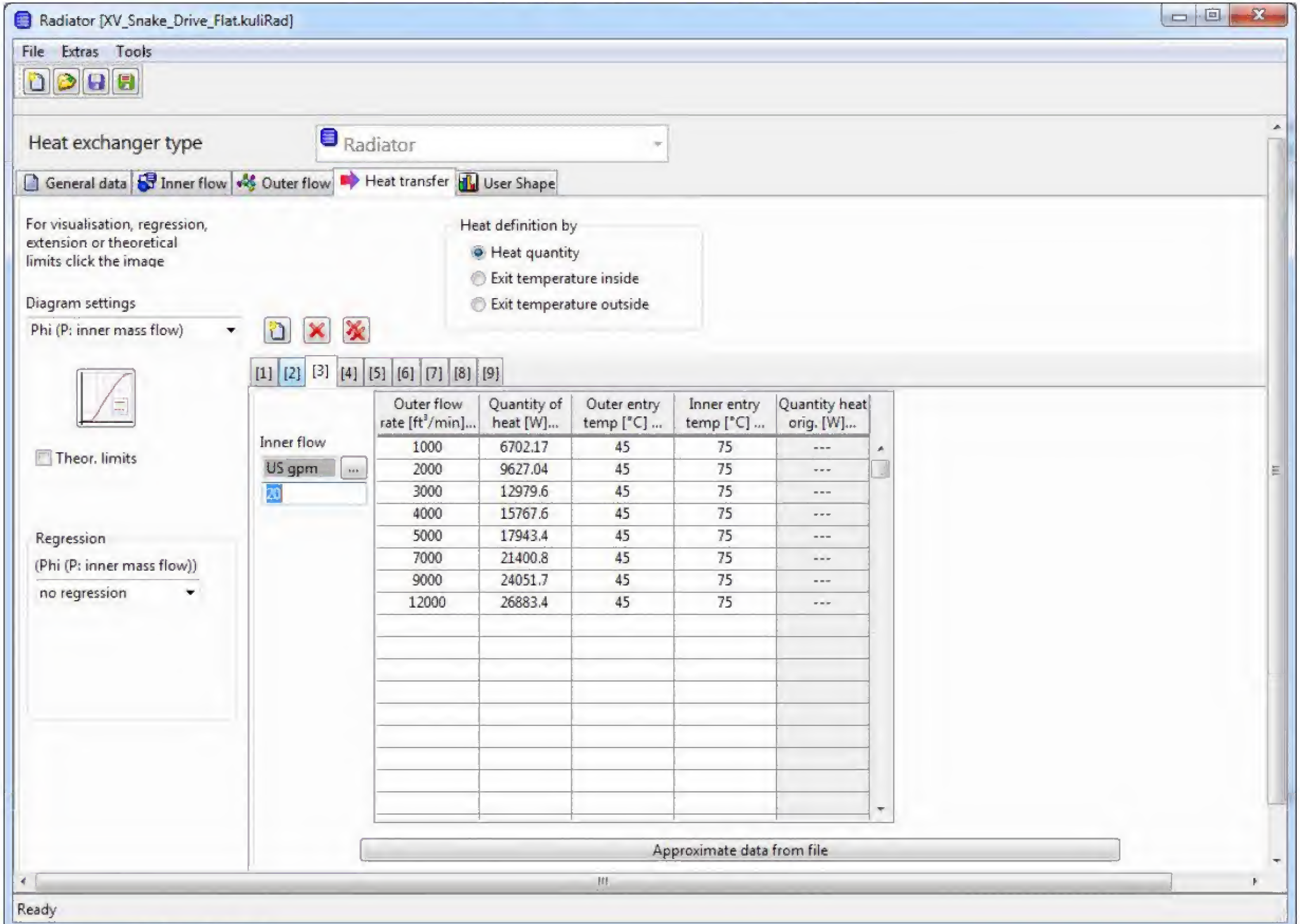
Approximate data from file

Ready

XV_Snake_

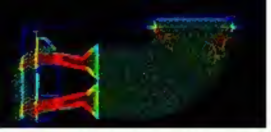
EGW Radiator Parameters – Engine, 85C, 70C



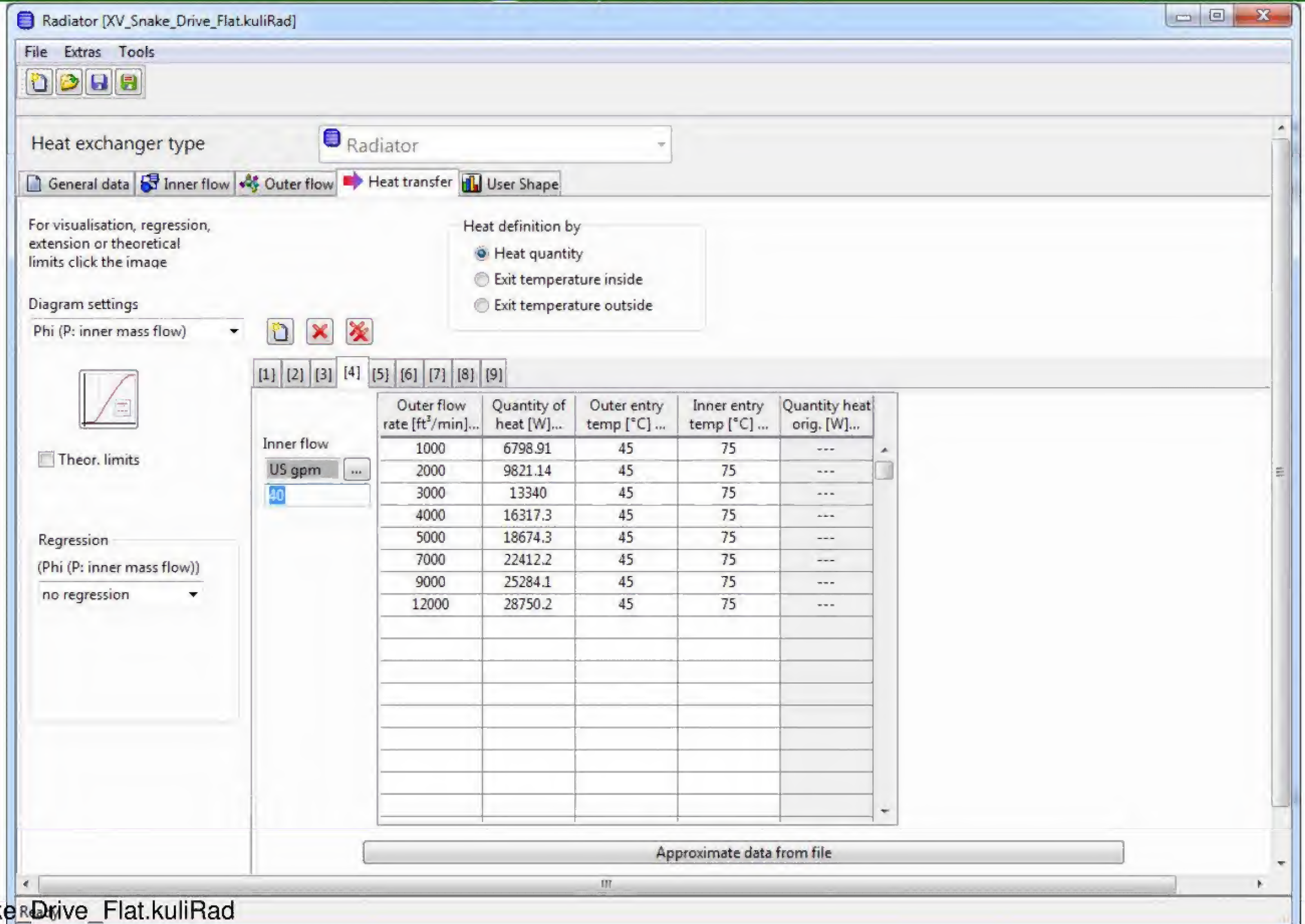


Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	6702.17	45	75	---
2000	9627.04	45	75	---
3000	12979.6	45	75	---
4000	15767.6	45	75	---
5000	17943.4	45	75	---
7000	21400.8	45	75	---
9000	24051.7	45	75	---
12000	26883.4	45	75	---

XV_Snake_Drive_Flat.kuliRad

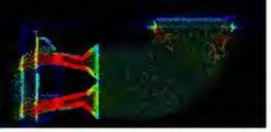


EGW Radiator Parameters – Engine, 85C, 70C

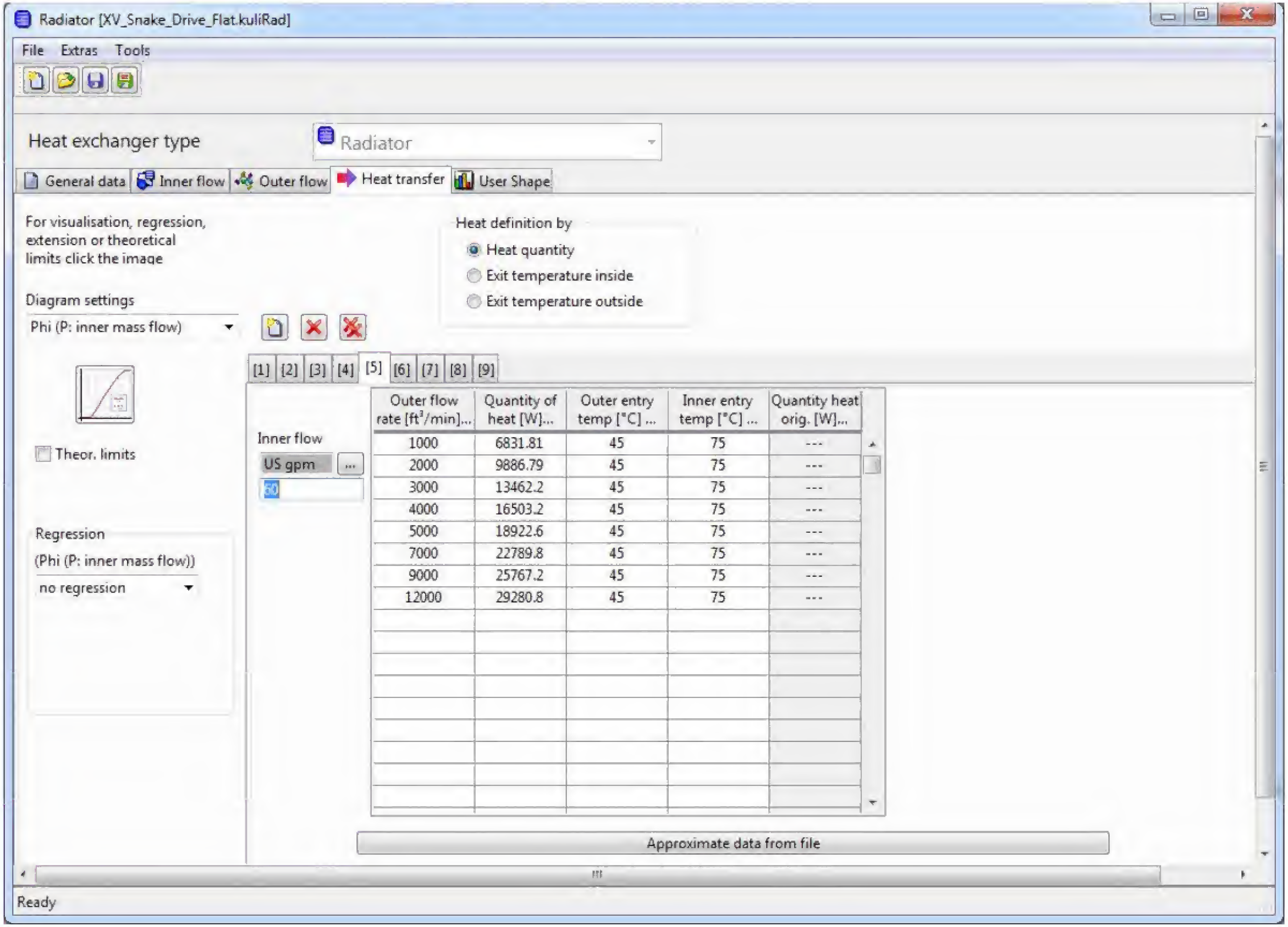


Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	6798.91	45	75	---
2000	9821.14	45	75	---
3000	13340	45	75	---
4000	16317.3	45	75	---
5000	18674.3	45	75	---
7000	22412.2	45	75	---
9000	25284.1	45	75	---
12000	28750.2	45	75	---

XV_Snake_Drive_Flat.kuliRad

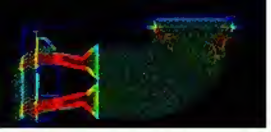


EGW Radiator Parameters – Engine, 85C, 70C

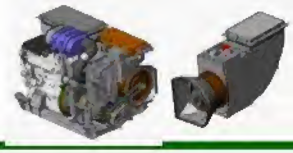


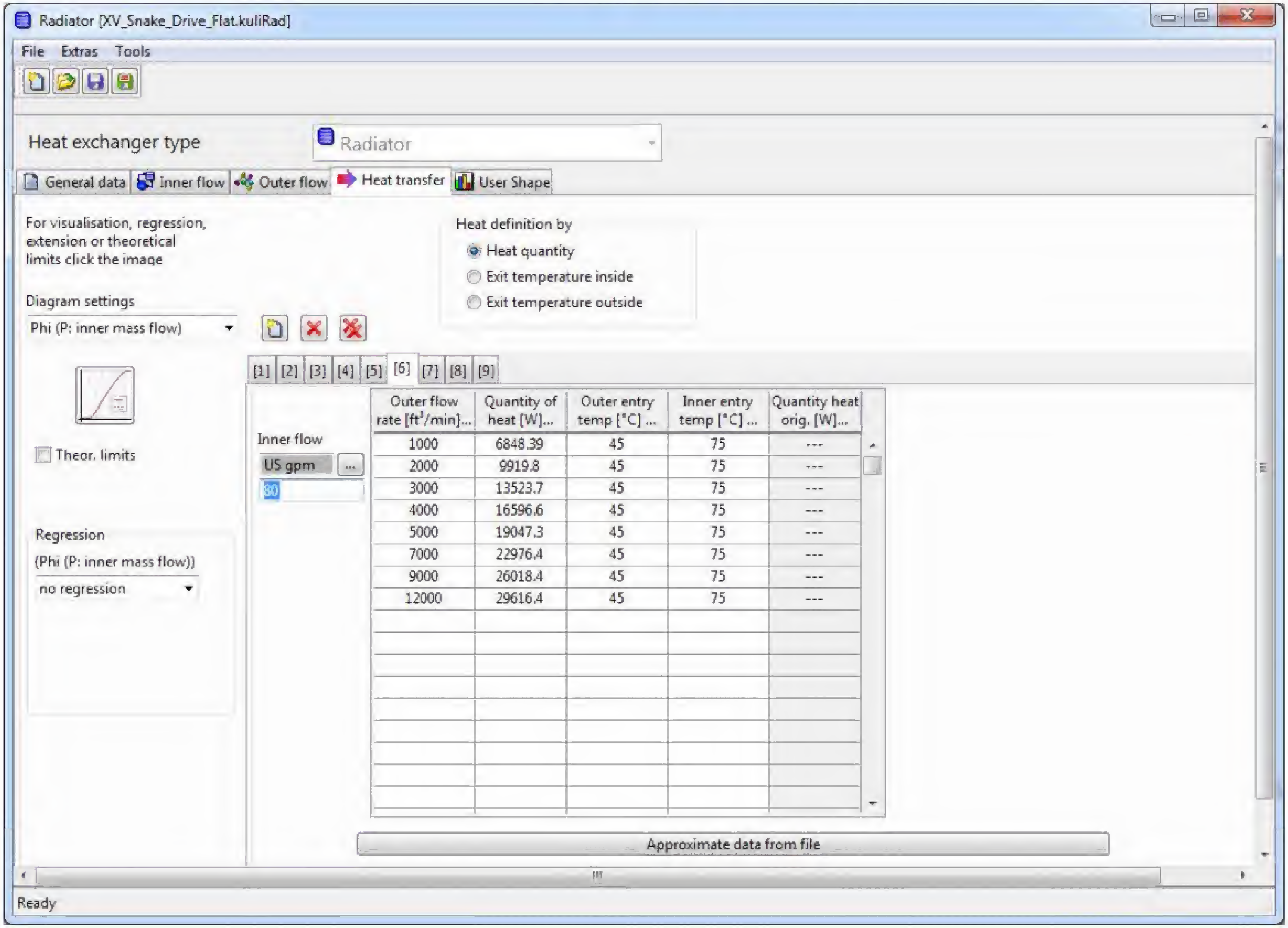
Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	6831.81	45	75	---
2000	9886.79	45	75	---
3000	13462.2	45	75	---
4000	16503.2	45	75	---
5000	18922.6	45	75	---
7000	22789.8	45	75	---
9000	25767.2	45	75	---
12000	29280.8	45	75	---

XV_Snake_Drive_Flat.kuliRad

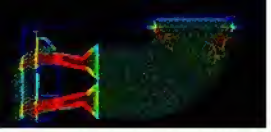


EGW Radiator Parameters – Engine, 85C, 70C

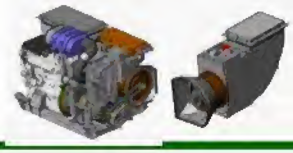


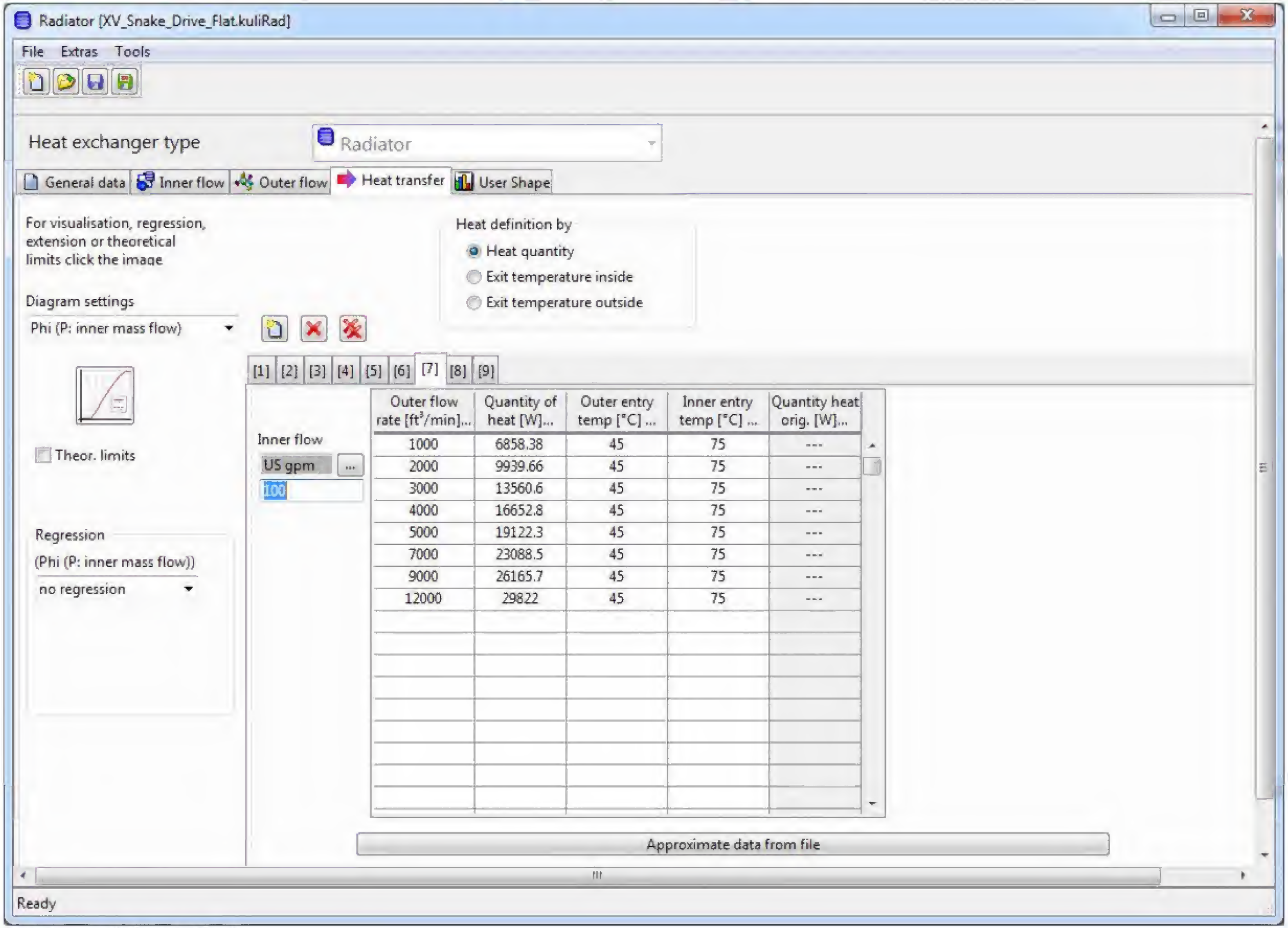


XV_Snake_Drive_Flat.kuliRad



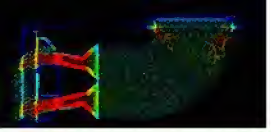
EGW Radiator Parameters – Engine, 85C, 70C



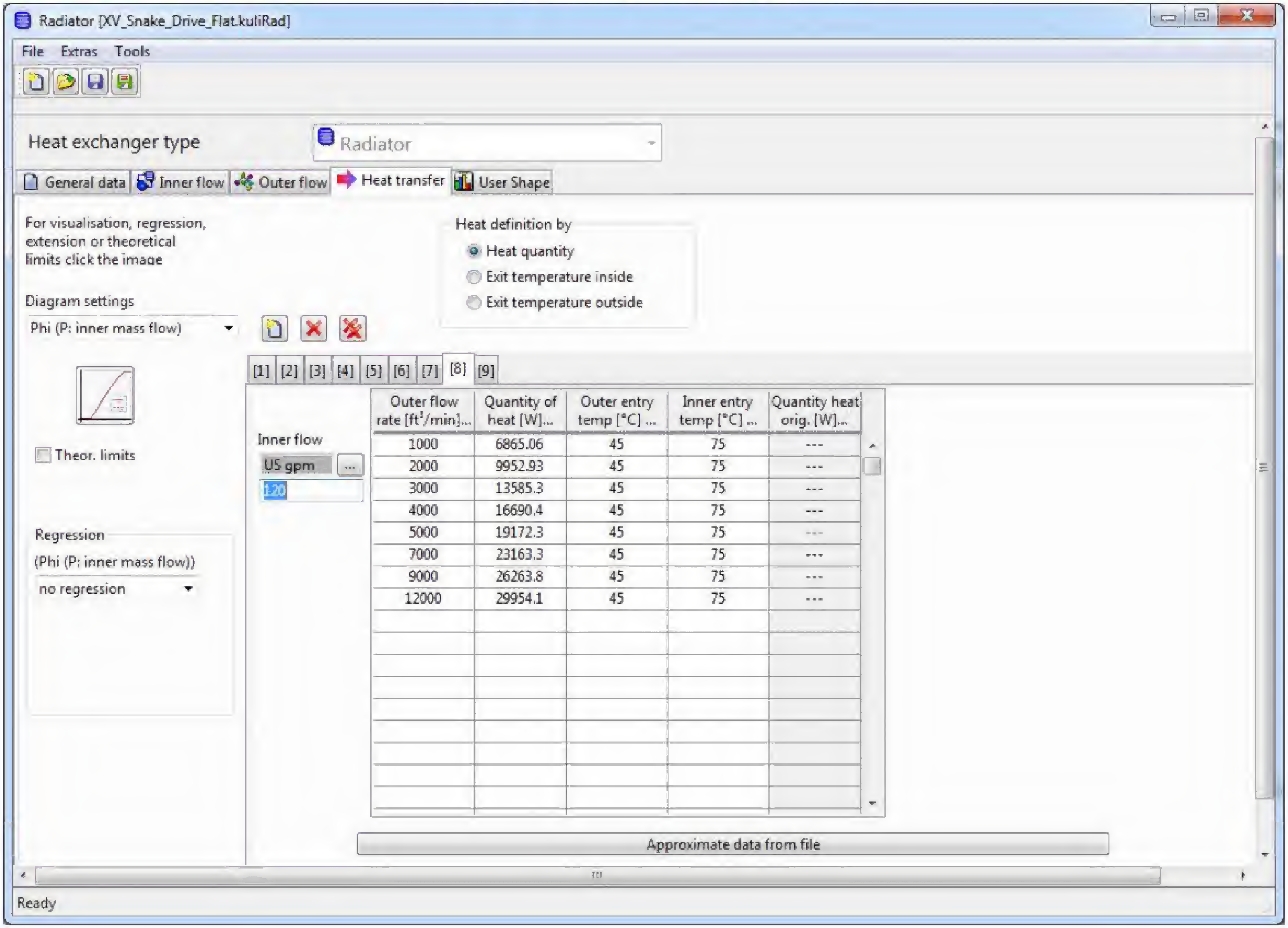


Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	6858.38	45	75	---
2000	9939.66	45	75	---
3000	13560.6	45	75	---
4000	16652.8	45	75	---
5000	19122.3	45	75	---
7000	23088.5	45	75	---
9000	26165.7	45	75	---
12000	29822	45	75	---

XV_Snake_Drive_Flat.kuliRad

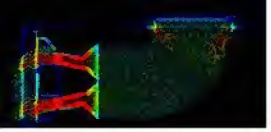


EGW Radiator Parameters – Engine, 85C, 70C

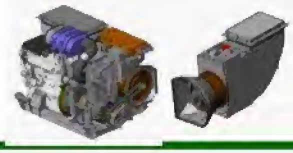


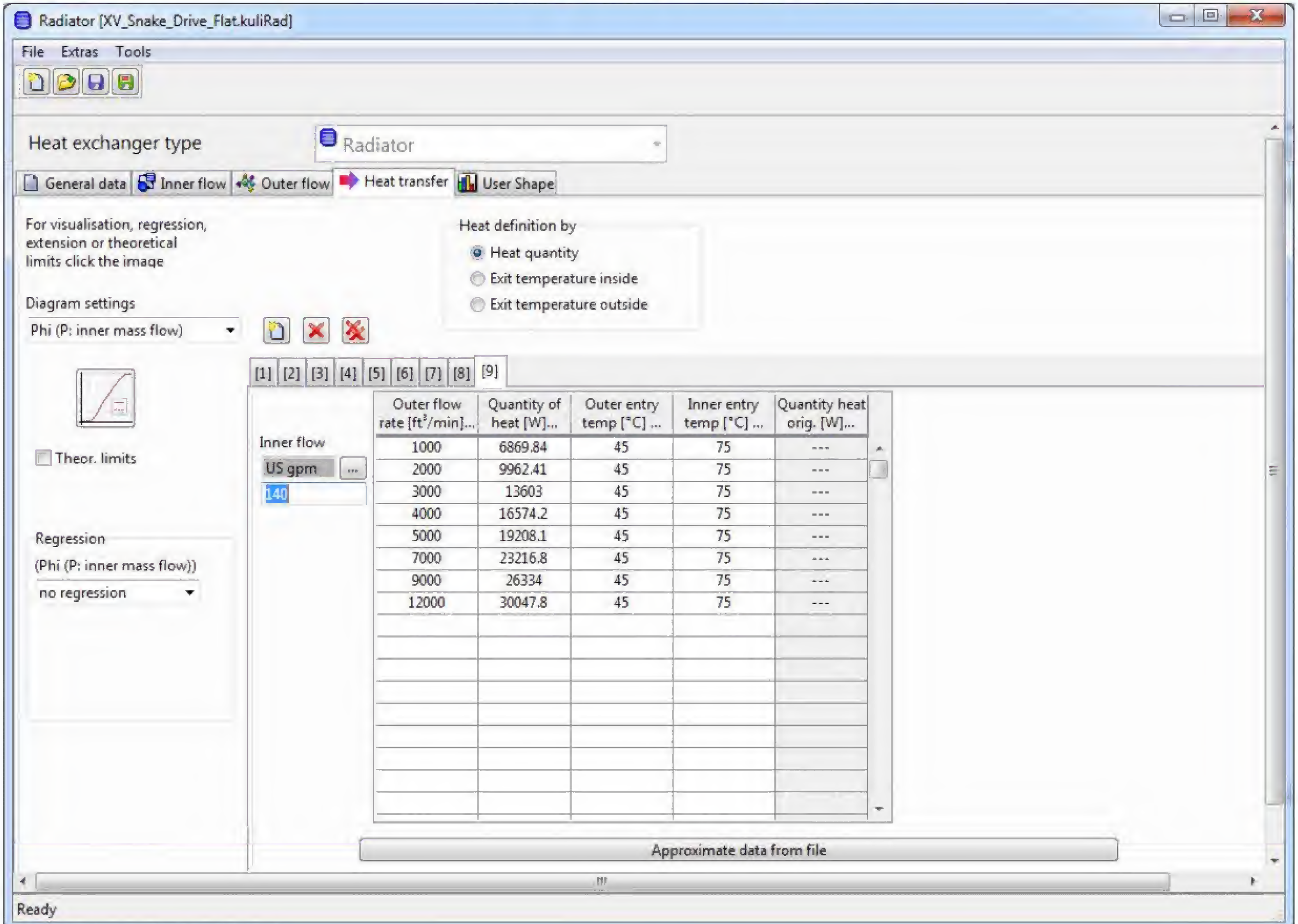
Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	6865.06	45	75	---
2000	9952.93	45	75	---
3000	13585.3	45	75	---
4000	16690.4	45	75	---
5000	19172.3	45	75	---
7000	23163.3	45	75	---
9000	26263.8	45	75	---
12000	29954.1	45	75	---

XV_Snake_Drive_Flat.kuliRad



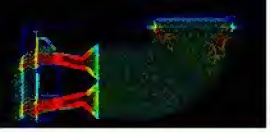
EGW Radiator Parameters – Engine, 85C, 70C



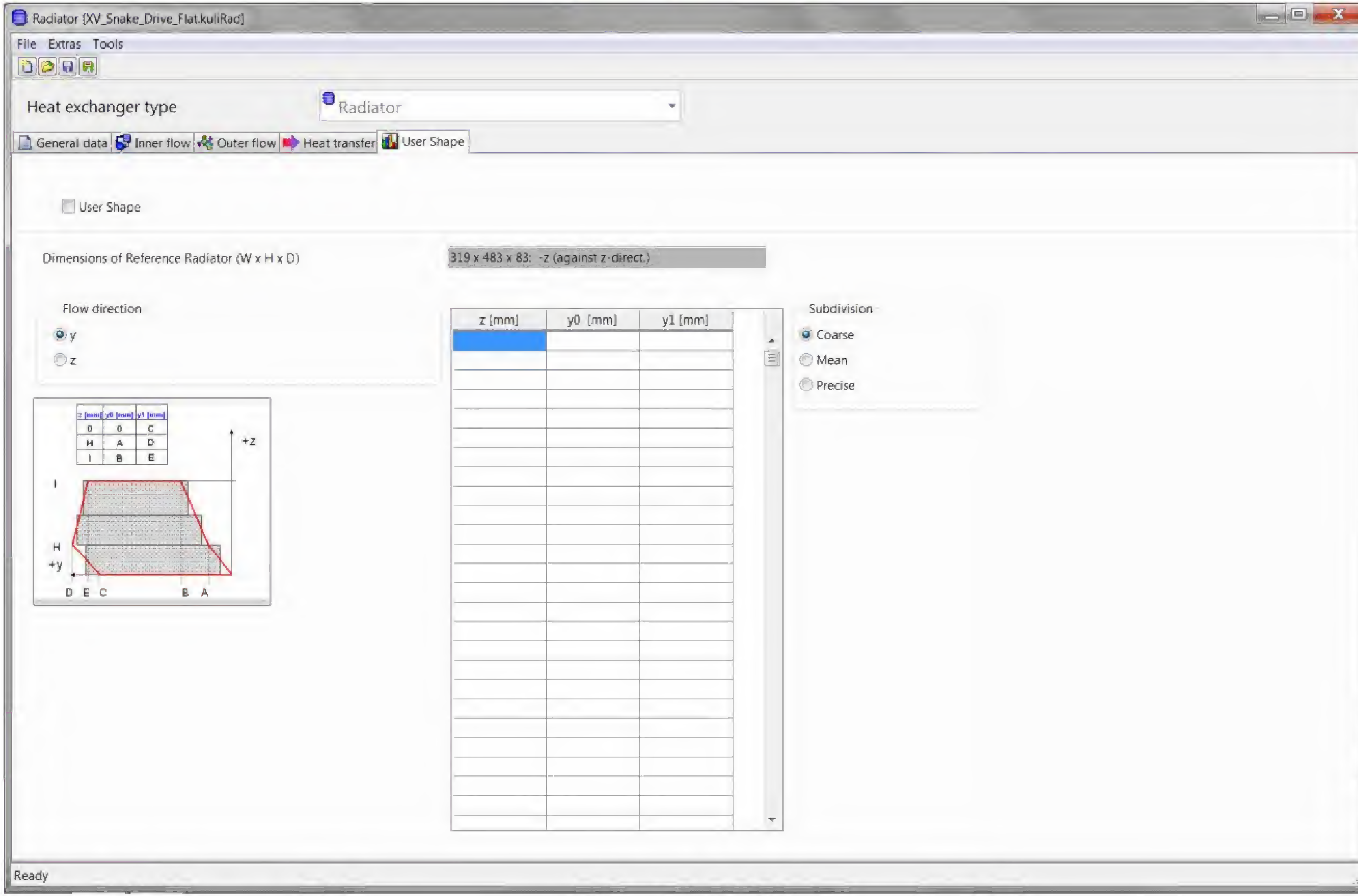


Outer flow rate [ft³/min]...	Quantity of heat [W]...	Outer entry temp [°C] ...	Inner entry temp [°C] ...	Quantity heat orig. [W]...
1000	6869.84	45	75	---
2000	9962.41	45	75	---
3000	13603	45	75	---
4000	16574.2	45	75	---
5000	19208.1	45	75	---
7000	23216.8	45	75	---
9000	26334	45	75	---
12000	30047.8	45	75	---

XV_Snake_Drive_Flat.kuliRad



EGW Radiator Parameters – Engine, 85C, 70C



XV_Snake_Drive_Flat.kuliRad

THERMAL MANAGEMENT OF THE EXPERIMENTAL VEHICLE (XV)

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TABLE OF CONTENTS

Overview

Thermal management was a critical item on the Experimental Vehicle (XV) development. Successful demonstration of key, high-power, mobility requirements at or near the objective ambient temperature of 45 C would be indicative of the viability of ground vehicles of XV's class in today's combat environments. Continuous, steady-state stressing cases are the most important drivers of thermal management system design. The commitment to this goal was evident as the XV thermal management design target never wavered from system that would support all mobility requirements at 45 C ambient with ballistic grills, even though full capability at 25 C without ballistic grills was the contractual requirement. A further testament was the inclusion of over a week's worth of high power testing at ambient conditions up to 45 C in the a temperature controlled chassis dynamometer test. In that, the XV vehicle successfully demonstrated its most thermally demanding mobility requirements at temperatures just shy of 45 C. Further, during mobility testing at an outdoor environment, where temperatures reached 43 C, the XV experienced no thermal faults after appropriate system maintenance procedures were adopted.

Design Challenges

Designing a thermal management system that would support all of the contractual mobility requirements and program objectives proved to be a significant challenge. Typical ground combat vehicle cooling system design hurdles, which were also common to XV include:

- High performance/mobility requires a significant amount of power, which produces significant heat
- Efficiently rejecting heat favors large unrestricted cooling air paths
- Military vehicles have limited volume available for cooling air paths, which must also be protected by ballistic grills
- Ballistic grills and small air path volumes restrict air flow and drive up required cooling fan power
- Higher ambient temperatures drive up required cooling fan power
- Available cooling fan power is finite and providing additional fan power produces additional heat

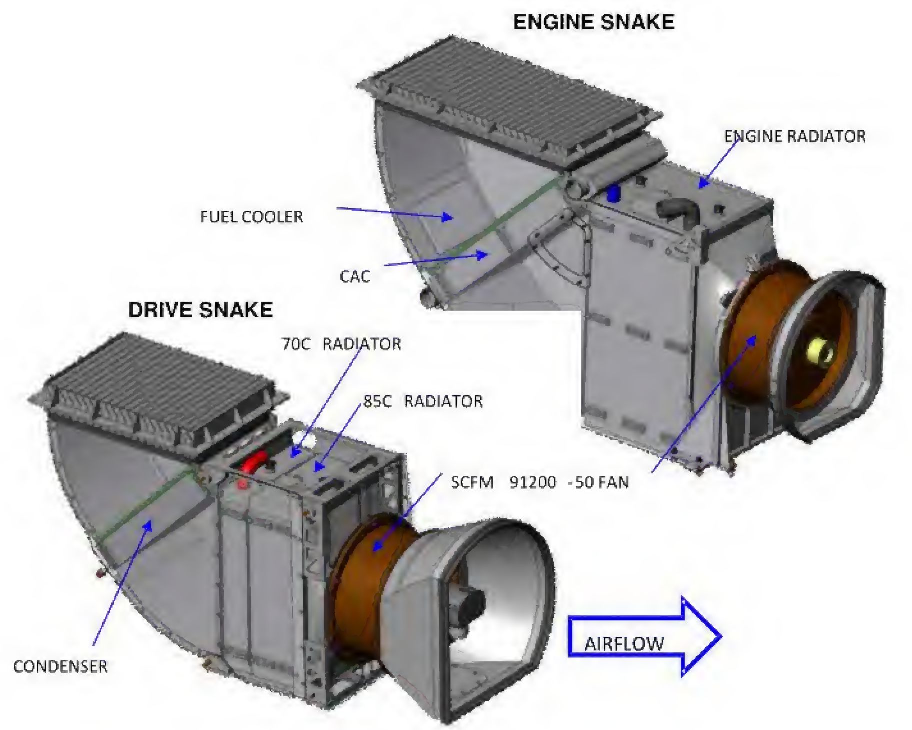
The result is that for a given vehicle with a finite power source, the available traction decreases as ambient temperature increases because the cooling fan requires additional power. In addition to this, several other factors challenged the designers of the XV thermal management system. They include:

- COTS electronics used for XV have lower maximum operating temperatures than their military grade counterparts
- Hybrid-Electric drive components (Motors/Generators and controllers) have lower maximum operating temperatures than purely mechanical drive system (Engine-Transmission)
- Hybrid-Electric drive trains reject more heat than a purely mechanical drive trains
- Component coolant temperature requirements vary significantly (10 C for batteries and electronics to 95 C for the engine)
- Over 30 components or enclosures required cooling complicating system design and integration
- Small order volumes limited the number of interested suppliers for custom components (Fans, Radiators, etc.)

To tackle these design challenges and produce a robust research platform that also demonstrated the combat viability of an XV-like vehicle, a variety of cooling topologies incorporating various features and characteristics were considered. Two of the key features traded include:

- Number of liquid cooling circuits (coolant temperatures)
  - More cooling loops yield maximum efficiency (low cooling power consumption) over a range of operating conditions
  - Less cooling loops for simpler design and integration
- Number of cooling air paths and/or fans
  - Multiple cooling air paths/fans yield maximum efficiency over a range of operating conditions; especially engine off/battery only (“silent” mobility)
  - Single cooling air path/fan for simpler design and integration

Candidate topologies were evaluated against a variety of weighted metrics to select the best thermal management approach. The two finalists were the Dual Snake (two air paths each with their own fan) and the Traditional (single air path with one or more fans). Each of these candidates contained five main cooling circuits. In the end, the Dual Snake topology was selected for its efficiency and versatility. It is described in the figures and tables below.



XV Engine and Drive Snake

AIRPATH 1 - Port Side (Drive Snake)		AIRPATH 2 - Starboard Side (Engine Snake)	
Heat Exchanger	**Design Heat Rejection and Coolant Spec**	**Heat Exchanger**	**Design Heat Rejection and Coolant Spec**
A/C System Condenser (Batteries and Misc Electronics)	10 kW - 40 LPM @ 10 C (Chilled Coolant)	*Single Pass Charge Air Cooler*	60 C (Air)
Single Pass Radiator (HV Electronics and Aux Motors/Generators)	12 kW - 225 LPM @ 70 C	*Quad Pass Radiator (Engine and Brake Shunt Resistor)*	120 kW - 180 LPM @ 95 C (Coolant)
Dual Pass Radiator (Wheel Motors and Main Generator)	35 kW - 85 LPM @ 85 C		
Fan Airflow Estimate	**Fan Power**	**Fan Airflow Estimate**	**Fan Power**
5100 SCFM @ 6100 RPM	10 kW Electrical @ 6100 RPM (Electric Motor Driven)	8600 SCFM @ 10,000 RPM	43 kW Mechanical @ 10,000 RPM (Electric Motor or Engine Drive; both via Belt)

Description

The air path architecture adopted for XV was a dual air path configuration termed the Dual Snake. It consists of two independent air paths (the Engine and Drive Snake) each with their own cooling fan. The Engine Snake provided engine cooling and the Drive Snake provided cooling for all electronic, electrical and hybrid-electric drive components. This architecture provided tremendous benefits including:

- High efficiency (low cooling power consumption per rate of heat rejection) over a range of operating conditions
- Engine-off/Silent-mobility benefits including
  - Low power consumption
  - Low fan noise

The XV thermal management system uses a 50/50 mixture of Ethylene Glycol and Water (EGW) as the primary means of distributing cooling throughout the vehicle. Testing with a 50/50 Propylene Glycol and water mixture

(PGW) was carried out in the SIL and the vehicle is compatible with both coolants. There are four different EGW cooling loops present on the vehicle that provide cooling to over 30 different components and enclosures. All components/enclosures are plumbed in parallel with the exception of the Brake Shunt Resistor and Engine which are plumbed in series. The engine's fuel and charge air are cooled directly by air without an EGW intermediary fluid. A description of the vehicle cooling loops, their capabilities and the components they cool is included in the table below.

DESCRIPTION OF COOLED COMPONENTS			
DRIVE SNAKE		ENGINER SNAKE	
SUB-AMBIENT LOOP		FUEL COOLER	
10 kiwi MAX - 40 LPM WGW MAX at 10 C NOMINAL		60 c MAX FUEL TEMP	
COMPONENT	QUANTITY	COMPONENT	QUANTITY
LV Electronics Enclosure	1	Engine Fuel (DF2 or JP8)	1
HV Electronics Enclosure	1		
Controller w/ Cold Plate	2		
Turret	1		
Battery Enclosure	2		
70C LOOP		CHARGE AIR COOLER	
12 kW MAX - 225 LPM EGW MAX at 70 C MAX		60 C MAX AIR TEMP	
COMPONENT	QUANTITY	COMPONENT	QUANTITY
Wheel Motor Controller	6	Engine Charge Air	1
Generator Controller	1		
Brake Chopper Shunt Controller	2		
350 V - 750 V Convertor	2		
350 V Motor/Generator	1		
Generator Controller	1		
Drive Snake Fan Motor	1		
350 V to 12/28 V Convertor	3		
85 C LOOP		ENGINE LOOP	
35 kW MAX - 85 LPM EGW MAX at 85 C MAX		20 KW MAX (Engine Only) - 180 LPM EGW MAX at 95 C MA	
COMPONENT	QUANTITY	COMPONENT	QUANTITY
Wheel Motor	6	Engine	1
750 V Generator	1	Brake Shunt Resistor (40 kW Max Expected)	1

The heat load, coolant flow rate and temperatures specified in this table were stated as follows:

SUB-AMBIENT LOOP

- Heat load is maximum anticipated (max vehicle load at 45 C ambient temperature with solar load) and was also the system's design capacity
- Coolant flow rate and temperature are the values expected to maintain all sub-ambient components at acceptable temperatures under worst case conditions; this was also the system's design performance

70 C LOOP

- Heat load is the maximum anticipated (80 kph @ 45 C) and was also the system's design capacity after fouling margin
- Coolant flow rate is the sum of the prescribed coolant flow rates for each of the components and was also the system's design flow rate
- Coolant temperature is the maximum coolant temperature prescribed for each of the components and was also the system's design temperature after fouling margin

85 C LOOP

- Heat load is the maximum anticipated (80 kph @ 45 C) and was also the system's design capacity after fouling margin
- Coolant flow rate is the sum of the prescribed coolant flow rates for each of the components and was also the systems design flow rate

- Coolant temperature is the maximum coolant temperature prescribed for each of the components and was also the system's design temperature after fouling margin

FUEL COOLER

- Maximum fuel temperature before the engine will begin to limit power and design temperature

CHARGE AIR COOLER

- Maximum charge air temperature before the engine will begin to limit power and design temperature after fouling margin

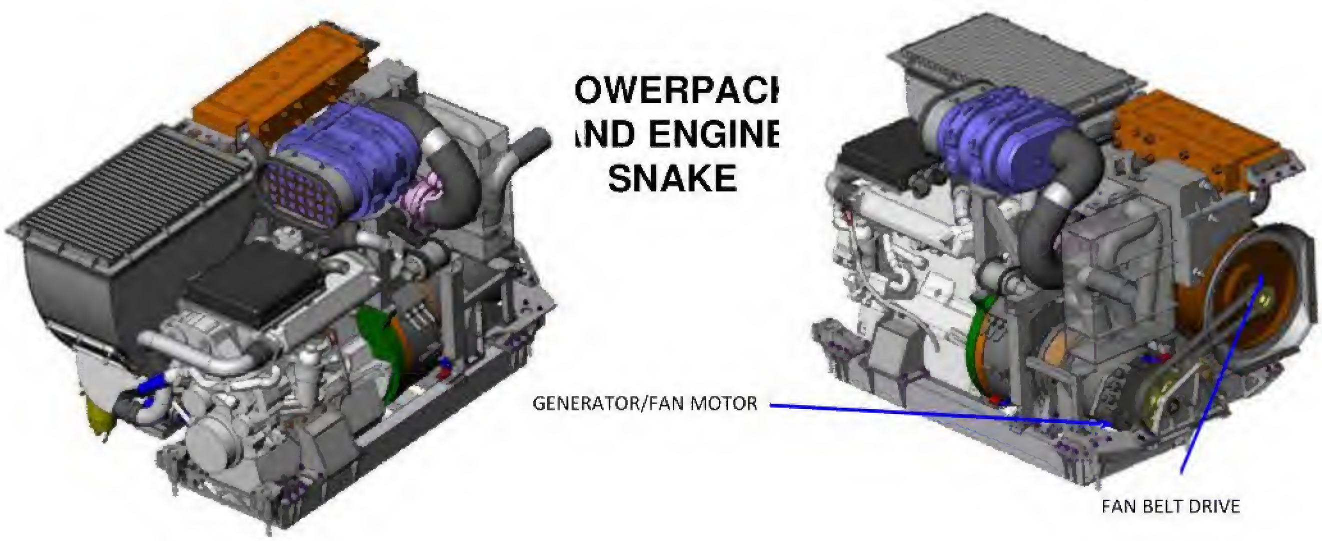
ENGINE LOOP

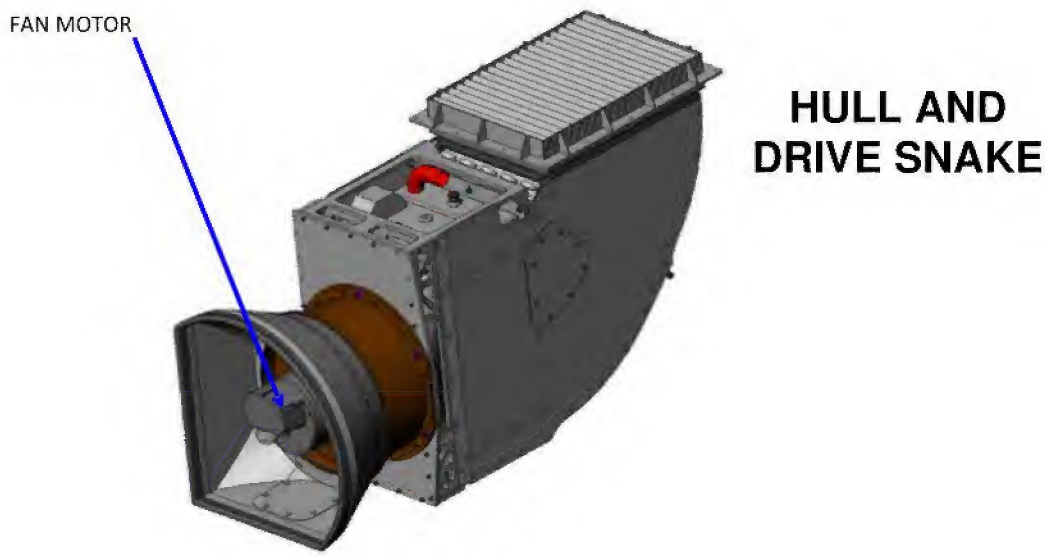
- Maximum expected engine heat rejection plus 20% margin over test data (added in case hot engine bay conditions led to additional engine to coolant heat rejection) and was also the system's design capacity after fouling margin
- Maximum measured engine coolant flow rate
- Prescribed shunt coolant inlet temperature
- Engine coolant inlet temperature predicted to achieve adequate cooling at maximum engine output power (the engine will limit power if the coolant outlet temperature reaches 105 C) after fouling margin and 20% additional engine to coolant heat rejection

Note that all of the heat rates mentioned in this table are the maximum continuous heat rates expected based on test or manufacturers data. Intermittent heat rates may exceed these values, but were not a significant factor in thermal management system design.

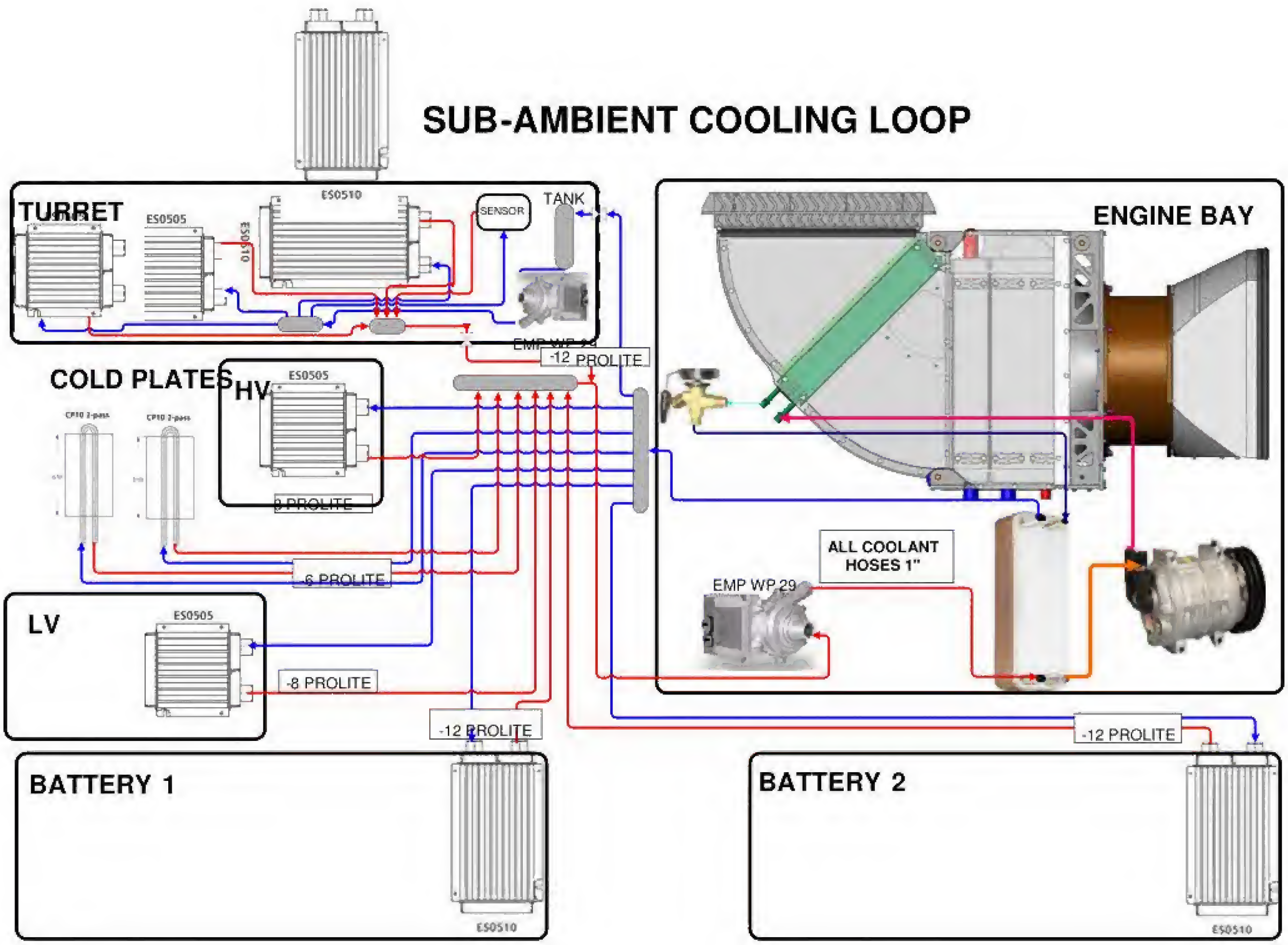
Physical System Description

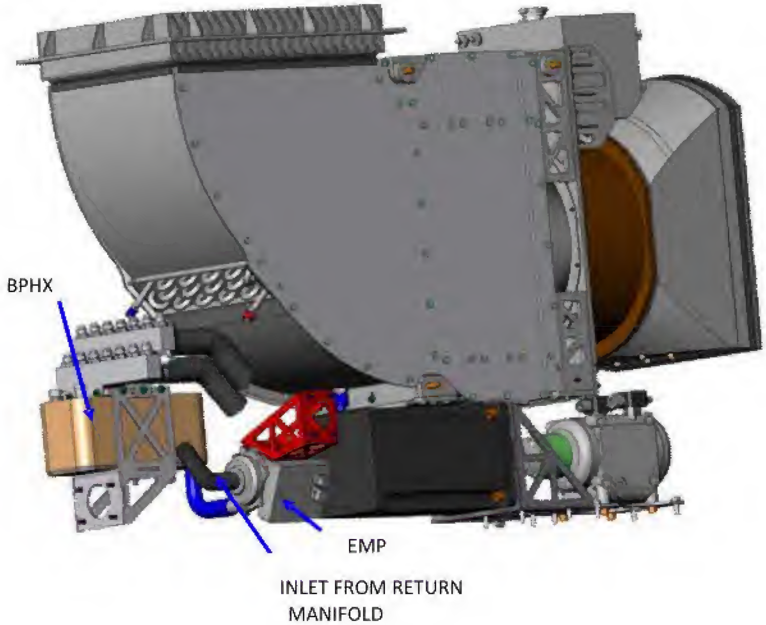
The Engine and Drive Snakes are located on either side of the engine. The Engine Snake is an integral part of the Power Pack while the Drive Snake mounts to the hull of the vehicle.

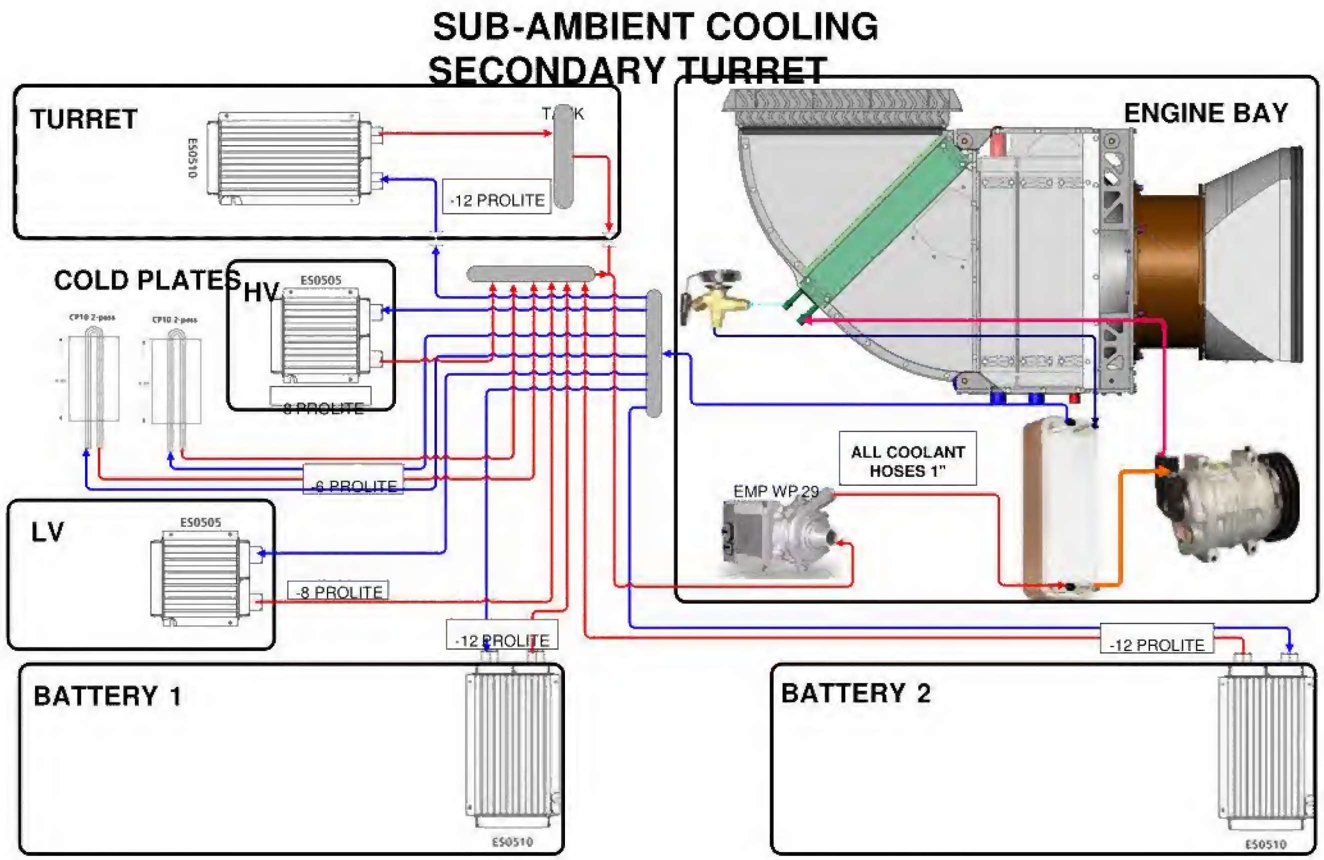




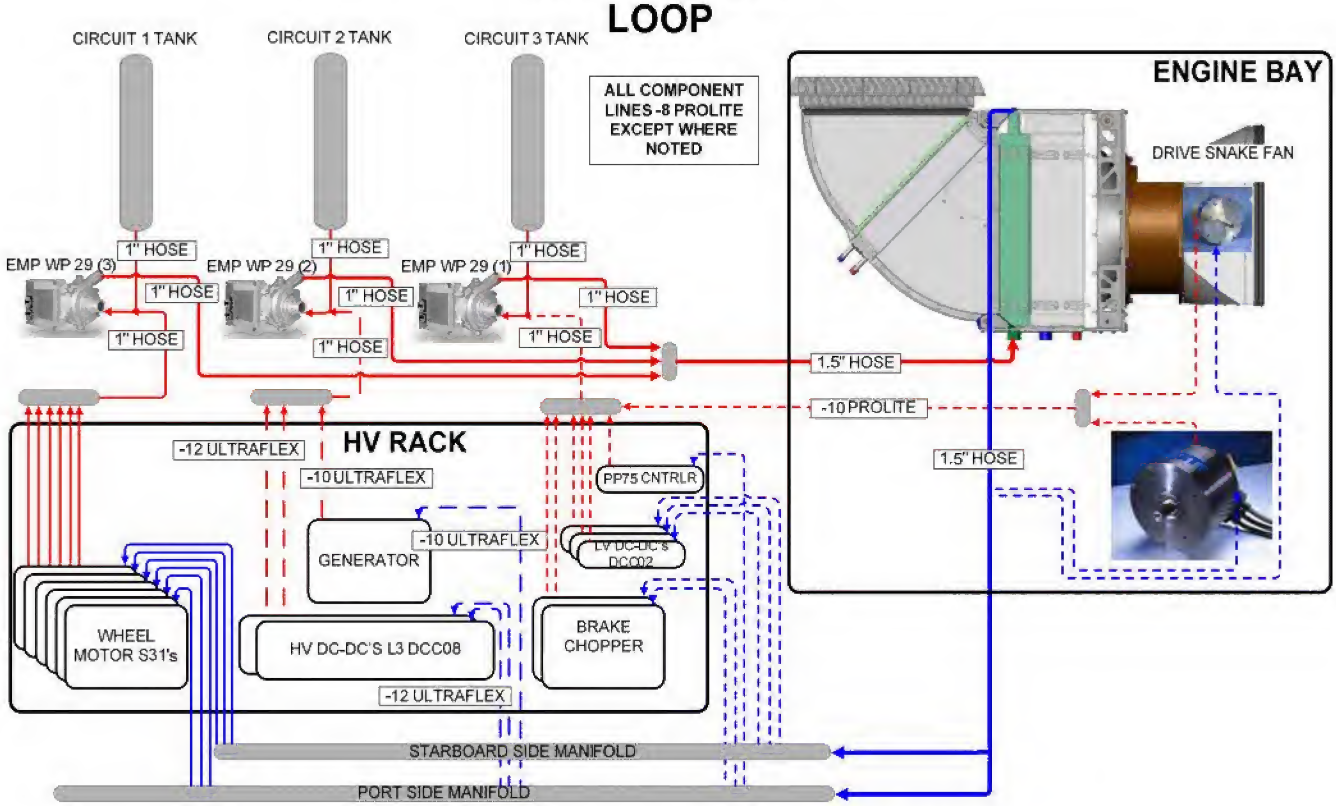
The integration of the Drive and Engine Snakes with the rest of the cooling system is shown in the schematics and images below. Many line sizes and component model numbers are noted on these schematics. Note that all components receiving EGW cooling are plumbed in parallel with the exception of the Engine and Brake Shunt Resistor.

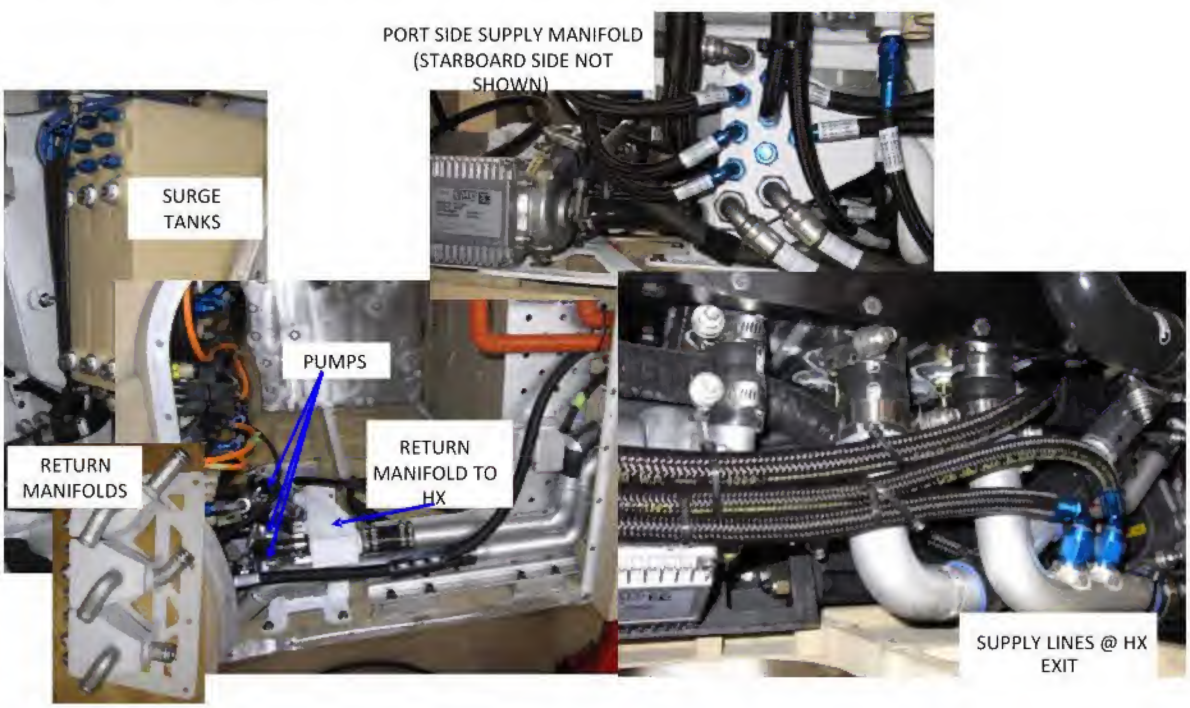

SUB-AMBIENT COOLING LOOP
TURRET
ES0510
ES0505
SENSOR
TANK
EMP WP 29
-12 PROLITE
ENGINE BAY
COLD PLATES
HV
ES0505
-8 PROLITE
-6 PROLITE
LV
ES0505
-8 PROLITE
ALL COOLANT HOSES 1"
EMP WP 29
-12 PROLITE
-12 PROLITE
BATTERY 1
ES0510
BATTERY 2
ES0510


BPHX
EMP
INLET FROM RETURN
MANIFOLD

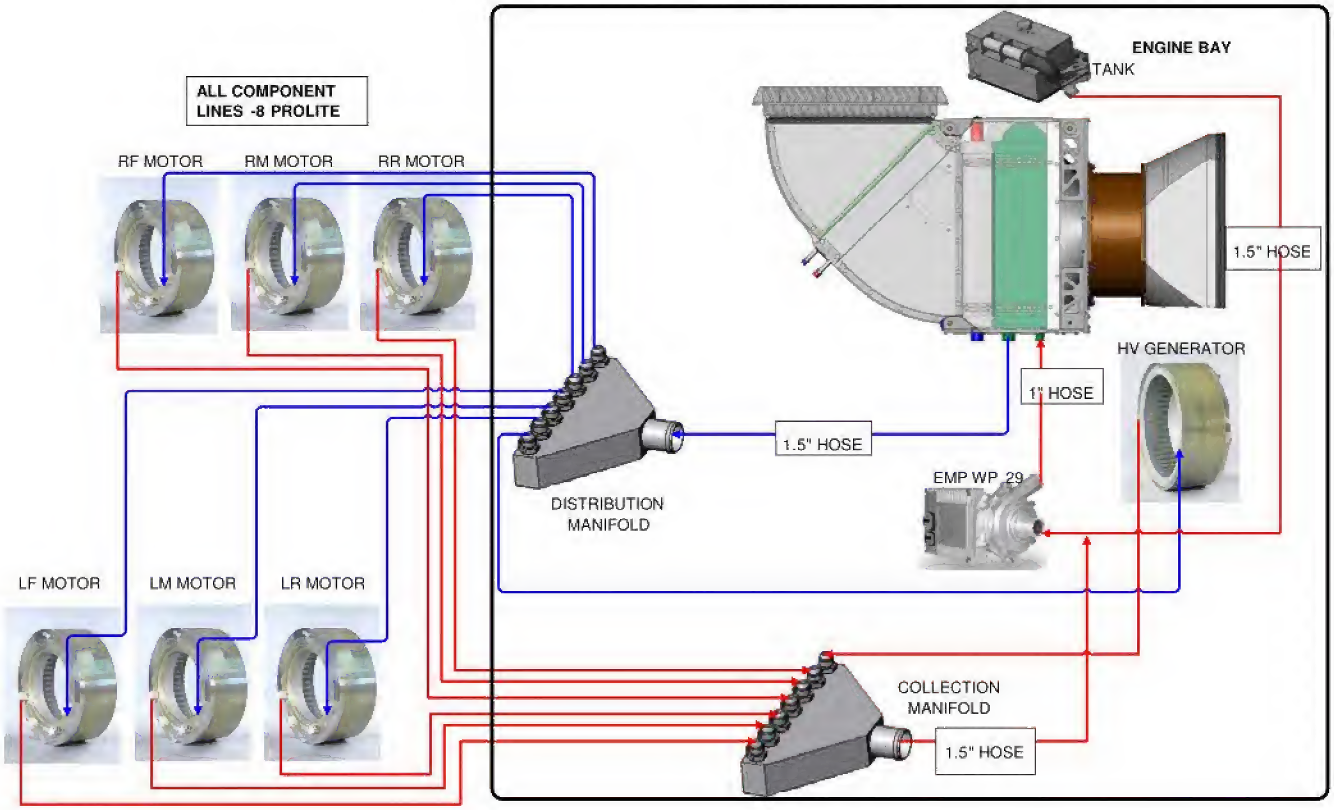

SUB-AMBIENT COOLING
SECONDARY TURRET
TURRET
ES0510
TANK
-12 PROLITE
ENGINE BAY
COLD PLATES
HV
ES0505
CP10 2-pass
CP10 2-pass
-8 PROLITE
-6 PROLITE
ALL COOLANT HOSES 1"
EMP WP 29
LV
ES0505
-8 PROLITE
-12 PROLITE
-12 PROLITE
BATTERY 1
ES0510
BATTERY 2
ES0510

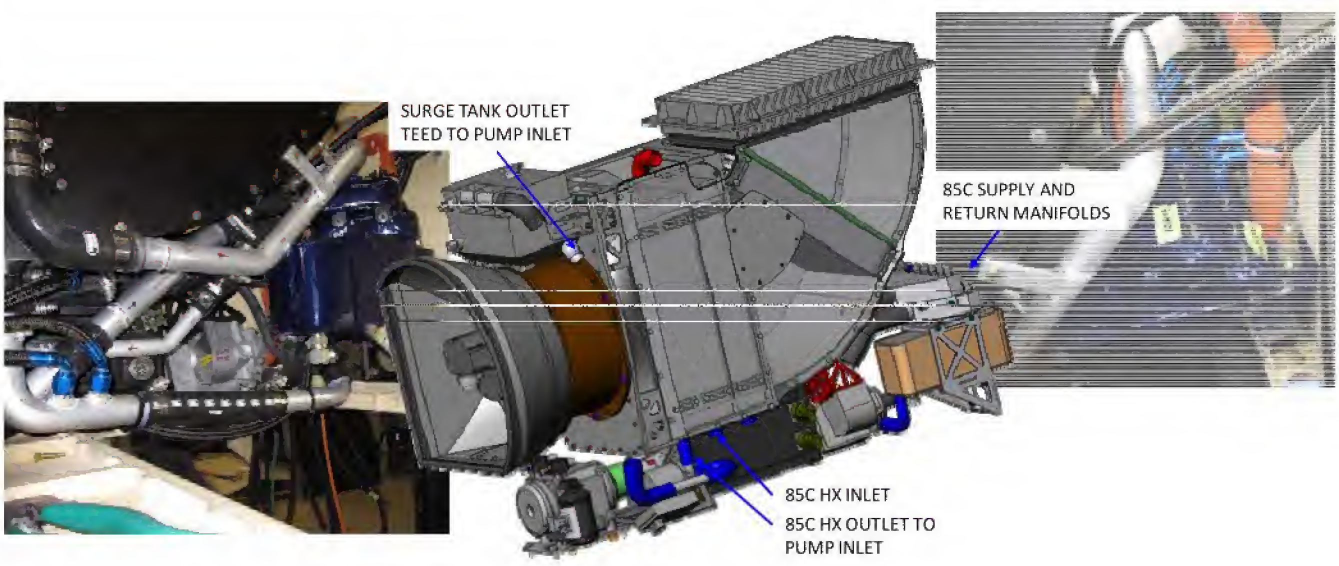
70 C COOLING LOOP



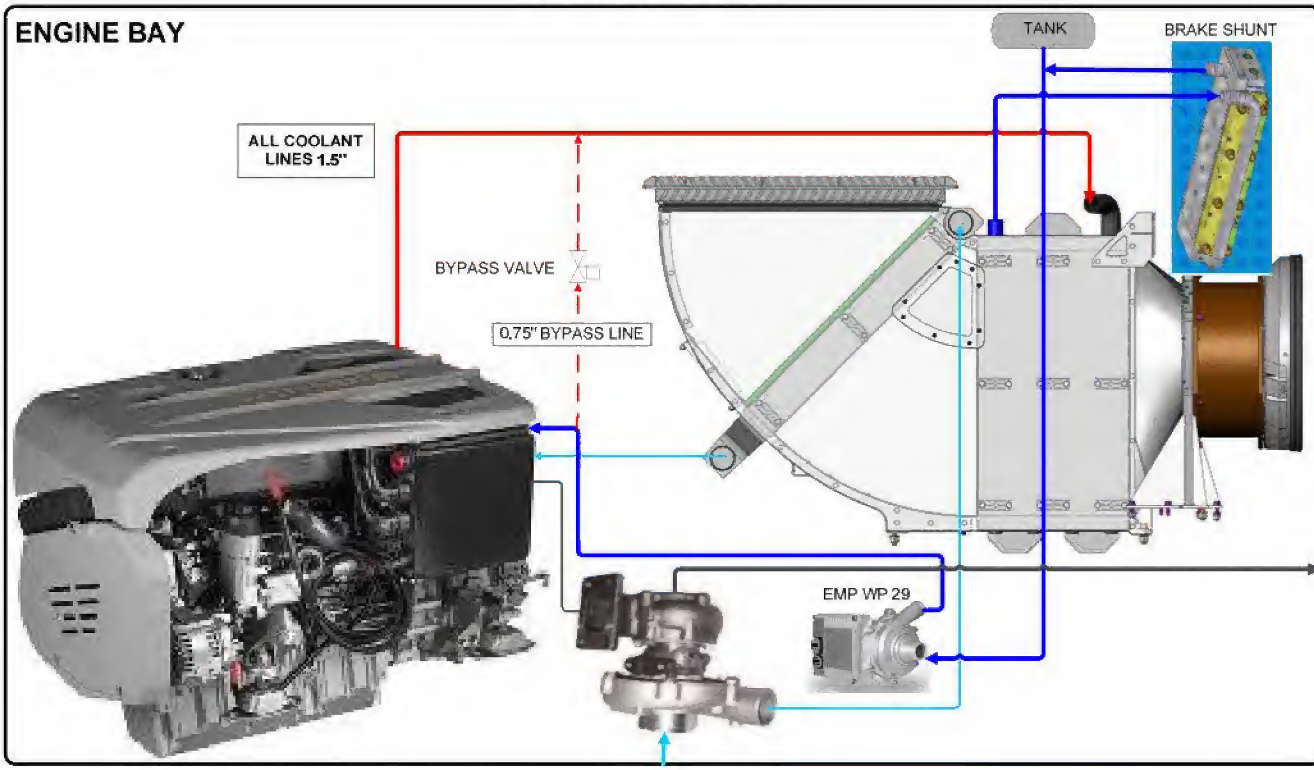


85 C COOLING LOOP





ENGINE COOLING LOOP



Significant Design Tools and Data

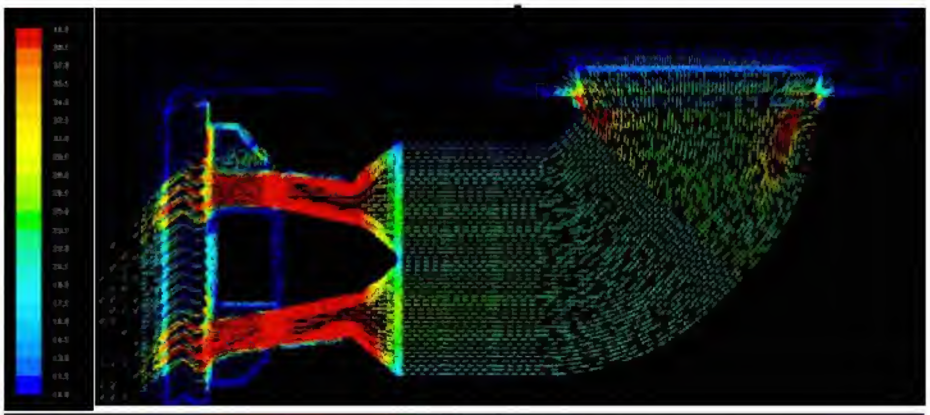
KULI AND SIMULINK

KULI is a one-dimensional thermal-fluid simulation software package with a block-diagram style GUI (http://www.kuli.at/). For the XV program it was used to rapidly model candidate cooling topologies, simulate their performance and investigate the effects of system modifications while fine-tuning the design. MATLAB-Simulink was used to model vehicle heat rejection from various components and this data was fed into KULI for thermal-fluid (cooling system performance) simulation. The results from KULI were component and fluid temperatures, air and coolant flow rates and required cooling fan powers.

FLUENT CFD

Fluent CFD models of candidate cooling air paths were developed and exercised by ThermalAnalytics. These simulations provided more accurate estimates of cooling fan power and heat exchanger performance than the KULI models. Data was routinely passed back and forth (in an offline fashion) between KULI and Fluent for model/simulation improvement.

DRIVE SNAKE VELOCITY VECTORS (M/S)



SUPPLIER AND TEST DATA

Various data sources were used to support the simulations used to design and fine-tune the XV cooling system. Supplier data such as pump and fan curves and motor and controller efficiency data was supplemented with test data. This all served to generate more accurate cooling system performance estimates.

FULL VEHICLE THERMAL MODEL

ThermalAnalytics developed a full vehicle thermal model using their own software packages to help predict temperatures and heat rejection rates inside the vehicle. This model included solar loading. The results were estimates of the heat that would infiltrate the sub-ambient enclosures (and in turn must be carried away by the sub-ambient cooling system) and the effect adding insulation to these enclosures would have. This model was also able to predict the total solar heat load on the vehicle, temperatures inside the turret where sensitive electronics would be housed and the temperature inside the engine bay.

Performance Summary

XV testing on a chassis dynamometer was the most valuable indicator of the XV thermal management system's ability to meet its cooling objectives under the harshest of conditions. Subsequent testing in the field provided valuable data regarding the system's ability to provide adequate cooling under the most extreme field conditions the vehicle is expected to see in its lifetime. These included high ambient temperatures, solar loading and extreme dust. Testing was also valuable to determine baseline performance of the system when compared to design calculations/simulations and actual vehicle performance. The PowerPack cooling tested at 45+C temperatures. At no time was field testing impacted by the performance of the XV thermal management system. Any maneuver that had the potential to cause a component to overheat was tested. A fouled or otherwise degraded system would support full capability at approximately 35 C or greater depending on the level of fouling/degradation.

ORDER FOR SUPPLIES OR SERVICES

1. CONTRACT/PURCH. ORDER/ AGREEMENT NO.	2. DELIVERY ORDER/CALL NO.	3. DATE OF ORDER/CALL (YYYYMMMDD)	4. REQ./PURCH. REQUEST NO.	5. PRIORITY
HR0011-11-P-0016		2011 Sep 02	7925/00	

6. ISSUED BY CODE HR0011
DARPA
CMO
ATTN: CHRISTOPHER GLISTA
3701 N. FAIRFAX DR.
ARLINGTON VA 22203

7. ADMINISTERED BY *(if other than 6)* CODE
SEE ITEM 6

8. DELIVERY FOB
[X] DESTINATION
[ ] OTHER
(See Schedule if other)

9. CONTRACTOR CODE 97688 FACILITY
NAME AND ADDRESS
CARNEGIE MELLON UNIVERSITY
5000 FORBES AVE
PITTSBURGH PA 15213-3815

10. DELIVER TO FOB POINT BY (Date) *(YYYYMMMDD)*
SEE SCHEDULE

11. MARK IF BUSINESS IS
[ ] SMALL
[ ] SMALL DISADVANTAGED
[ ] WOMEN-OWNED

12. DISCOUNT TERMS

13. MAIL INVOICES TO THE ADDRESS IN BLOCK
Wide Area Workflow (WAWF)

14. SHIP TO CODE HR0011
DARPA
PAUL EREMENKO
ATTN: TACTICAL TECHNOLOGY OFFICE
3701 NORTH FAIRFAX DRIVE
ARLINGTON VA 22203-1714

15. PAYMENT WILL BE MADE BY CODE HQ0347
DFAS INDIANAPOLIS CENTER
VENDOR PAY OFFICE - INDIANAPOLIS
8899 E. 56TH STREET
INDIANAPOLIS IN 46249

MARK ALL PACKAGES AND PAPERS WITH IDENTIFICATION NUMBERS IN BLOCKS 1 AND 2.

16. TYPE OF ORDER

DELIVERY/CALL		This delivery order/call is issued on another Government agency or in accordance with and subject to terms and conditions of above numbered contract.
PURCHASE	X	Reference your quote dated 2011 Jul 18 Furnish the following on terms specified herein. REF:

ACCEPTA (b)(4); (b)(6) [redacted] S THE OFFER REPRESENTED BY THE NUMBERED PURCHASE ORDER AS [redacted] OW MODIFIED, SUBJECT TO ALL OF THE TERMS AND CON [redacted] FOR (b)(4); (b)(6) [redacted]

Carnegie Mellon University

NAME OF CONTRACTOR — TYPED NAME AND TITLE — DATE SIGNED *(YYYYMMMDD)* 9-2-11

[X] If this box is marked, supplier must sign Acceptance and return the following number of copies: 1

17. ACCOUNTING AND APPROPRIATION DATA/ LOCAL USE
See Schedule

18. ITEM NO	19. SCHEDULE OF SUPPLIES/ SERVICES	20. QUANTITY ORDERED/ ACCEPTED*	21. UNIT	22. UNIT PRICE	23. AMOUNT
	SEE SCHEDULE				

* If quantity accepted by the Government is same as quantity ordered, indicate by X. If different, enter actual quantity accepted below quantity ordered and encircle.

24. UNITED STATES OF AMERICA (b)(6) [redacted]
TEL:
EMAIL: christopher.glista [redacted]
BY: (571) 218 4405 [redacted] FFICER

25. TOTAL $94,999.00
26. DIFFERENCES

27a. QUANTITY IN COLUMN 20 HAS BEEN
[ ] INSPECTED [ ] RECEIVED [ ] ACCEPTED, AND CONFORMS TO THE CONTRACT EXCEPT AS NOTED

b. SIGNATURE OF AUTHORIZED GOVERNMENT REPRESENTATIVE
c. DATE *(YYYYMMMDD)*
d. PRINTED NAME AND TITLE OF AUTHORIZED GOVERNMENT REPRESENTATIVE

e. MAILING ADDRESS OF AUTHORIZED GOVERNMENT REPRESENTATIVE
28. SHIP NO.
29. DO VOUCHER NO.
30. INITIALS
[ ] PARTIAL
[ ] FINAL
32. PAID BY
33. AMOUNT VERIFIED CORRECT FOR
f. TELEPHONE NUMBER
g. E-MAIL ADDRESS
31. PAYMENT
[ ] COMPLETE
[ ] PARTIAL
[ ] FINAL
34. CHECK NUMBER
36. I certify this account is correct and proper for payment.
a. DATE *(YYYYMMMDD)*
b. SIGNATURE AND TITLE OF CERTIFYING OFFICER
35. BILL OF LADING NO.
37. RECEIVED AT
38. RECEIVED BY
39. DATE RECEIVED *(YYYYMMMDD)*
40. TOTAL CONTAINERS
41. S/R ACCOUNT NO.
42. S/R VOUCHER NO.

Section 18-23 - ADDITIONS TO DD FORM 1155

ITEM NO.	SUPPLIES/SERVICES	QUANTITY	UNIT	UNIT PRICE	AMOUNT
0001		1		$94,999.00	$94,999.00
	META Program Component Model Library FFP The Contractor shall support DARPA/TTO's META program in accordance with the Statement of Work - Attachment 1, dated July 18, 2011. FOB: Destination				
				NET AMT	$94,999.00

ITEM NO.	SUPPLIES/SERVICES	QUANTITY	UNIT	UNIT PRICE	AMOUNT
000101					$0.00
	Funding for CLIN 0001 FFP Funding for CLIN 0001 FOB: Destination AO No. 7925/00				
				NET AMT	$0.00
	ACRN AA CIN: 000000000000000000000000000000				$94,999.00

INSPECTION AND ACCEPTANCE TERMS

Supplies/services will be inspected/accepted at:

CLIN	INSPECT AT	INSPECT BY	ACCEPT AT	ACCEPT BY
0001	Destination	Government	Destination	Government
000101	Destination	Government	Destination	Government

DELIVERY INFORMATION

CLIN	DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
0001	POP 02-SEP-2011 TO 03-JAN-2012	N/A	DARPA PAUL EREMENKO ATTN: TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 571-218-4889 FOB: Destination	HR0011
000101	N/A	N/A	N/A	N/A

ACCOUNTING AND APPROPRIATION DATA

AA: 9710400 1320 7925 P1M30 2525 DPAC 1 5362 S12136 62303E
AMOUNT: $94,999.00
CIN 000000000000000000000000000000: $94,999.00

CLAUSES INCORPORATED BY FULL TEXT

1. INSPECTION AND ACCEPTANCE

Inspection and acceptance shall be made at destination by the receiving activity.

2. PERFORMANCE

The term of the Purchase Order shall be from September 2, 2011 through January 3, 2011.

3. PURCHASE ORDER ADMINISTRATIVE DATA

(a) Invoices for goods received or services rendered under this purchase order shall be submitted electronically through Wide Area Work Flow – Receipt and Acceptance (WAWF):

(1) Vendors that have never used WAWF shall follow the directions in the WAWF Vendor Getting Started Guide available at the following website: http://www.dfas.mil/contractorpay/electroniccommerce/wideareaworkflow.html. This website also contains

links for Vendor training and practice. Additional support can be obtained by calling WAWF Customer Service at 866-618-5988.

(2) Back up documentation (such as timesheets, monthly status reports, etc.) can be included and attached to the invoice in WAWF. Attachments should be in PDF format, but Attachments created in any Microsoft Office product may be attached. Total limit for the size of files per invoice is 5 megabytes.

(b) The following information, regarding invoice routing DODAAC's, must be entered for completion of the invoice in WAWF:

WAWF Invoice Type:	2-in-1
Issuing Office DoDAAC	HR0011
Admin Offfice DoDAAC	HR0011
Service Acceptor DoDAAC	HR0011, extension 08
Paying Office DoDAAC	HQ0339

(c) For each invoice/cost voucher submitted for payment, the contractor shall also e-mail the WAWF automated invoice notice directly to the following points of contact:

Name	E-mail	Phone	Role
Chris Glista	christopher.glista@darpa.mil	(571) 218-4405	Contracting Officer
Paul Eremenko	paul.eremenko@darpa.mil	(571) 218-4889	META Program Manager

(d) Travel. All travel requests, other than local travel, shall be approved in advance by the Contracting Officer. All travel costs are subject to Public Law 99-234, FAR 31.205-46 (Deviation) and the Joint Travel Regulations.

4. PURCHASE ORDER CLAUSES

This Purchase Order incorporates the following clauses by reference, with the same force and effect as if they were given in full text.

CLAUSES INCORPORATED BY REFERENCE

FEDERAL ACQUISITION REGULATION (FAR) (48 CFR CHAPTER 1) CLAUSES:

52.204-7	Central Contractor Registration	OCT 2003
52.213-2	Invoices	APR 1984
52.213-4	Terms and Conditions - Simplified Acquisitions (Other Than Commercial Items)	APR 2005
52.232-25	Prompt Payment	OCT 2003
52.232-33	Payment by Electronic Funds Transfer—Central Contractor Registration	OCT 2003
52.242-15	Stop-Work Order	AUG 1989
52.243-1 Alt V	Changes Fixed-Price (Aug 1987) – Alternate V	APR 1984

The full text of a FAR clause may be accessed electronically at: http://www.arnet.gov/far/.

DEPARTMENT OF DEFENSE FAR SUPPLEMENT (DFARS) (48 CFR CHAPTER 2) CLAUSES:

252.204-7004	Central Contractor Registration (52.204-7) Alternate A	NOV 2003
252.204-7005	Oral Attestation of Security Responsibilities	NOV 2001
252.232-7003	Electronic Submission of Payment Requests	JAN 2004
252.235-7010	Acknowledgment Of Support and Disclaimer	MAY 1995
252.243-7001	Pricing of Contract Modifications	DEC 1991

The full text of a DFARS clause may be accessed electronically at http://www.acq.osd.mil/dpap/dars/dfars/.

CLAUSES INCORPORATED BY FULL TEXT

52.213-4 -- Terms and Conditions -- Simplified Acquisitions (Other Than Commercial Items) (May 2011)

(a) The Contractor shall comply with the following Federal Acquisition Regulation (FAR) clauses that are incorporated by reference:

(1) The clauses listed below implement provisions of law or Executive order:

(i) 52.222-3, Convict Labor (June 2003) (E.O. 11755).

(ii) 52.222-21, Prohibition of Segregated Facilities (Feb 1999) (E.O. 11246).

(iii) 52.222-26, Equal Opportunity (Mar 2007) (E.O. 11246).

(iv) 52.222-50, Combating Trafficking in Persons (Feb 2009) (22 U.S.C. 7104(g)).

(v) 52.225-13, Restrictions on Certain Foreign Purchases (Jun 2008) (E.o.s, proclamations, and statutes administered by the Office of Foreign Assets Control of the Department of the Treasury).

(vi) 52.233-3, Protest After Award (Aug 1996) (31 U.S.C. 3553).

(vii) 52.233-4, Applicable Law for Breach of Contract Claim (Oct 2004) (Pub. L. 108-77, 108-78).

(2) Listed below are additional clauses that apply:

(i) 52.204-10, Reporting Executive Compensation and First-Tier Subcontract Awards (Jul 2010) (Pub. L. 109) (31 U.S.C. 6101 note).

(ii) 52.232-1, Payments (Apr 1984).

(iii) 52.232-8, Discounts for Prompt Payment (Feb 2002).

(iv) 52.232-11, Extras (Apr 1984).

(v) 52.232-25, Prompt Payment (Oct 2008).

(vi) 52.233-1, Disputes (July 2002).

(vii) 52.244-6, Subcontracts for Commercial Items (Jan 2011).

(viii) 52.253-1, Computer Generated Forms (Jan 1991).

(b) The Contractor shall comply with the following FAR clauses, incorporated by reference, unless the circumstances do not apply:

(1) The clauses listed below implement provisions of law or Executive order:

(i) 52.222-19, Child Labor—Cooperation with Authorities and Remedies (Jul 2010) (E.O. 13126).(Applies to contracts for supplies exceeding the micro-purchase threshold.)

(ii) 52.222-20, Walsh-Healey Public Contracts Act (Oct 2010) (41 U.S.C. 35-45) (Applies to supply contracts over $15,000 in the United States, Puerto Rico, or the U.S. Virgin Islands).

(iii) 52.222-35, Equal Opportunity for Veterans (Sep 2010) (38 U.S.C. 4212) (Applies to contracts of $100,000 or more).

(iv) 52.222-36, Affirmative Action for Workers with Disabilities (Oct 2010) (29 U.S.C. 793) (Applies to contracts over $15,000, unless the work is to be performed outside the United States by employees recruited outside the United States.) (For purposes of this clause, *United States* includes the 50 States, the District of Columbia, Puerto Rico, the Northern Mariana Islands, American Samoa, Guam, the U.S. Virgin Islands, and Wake Island.)

(v) 52.222-37, Employment Reports on Veterans (Sep 2010) (38 U.S.C. 4212) (Applies to contracts of $100,000 or more).

(vi) 52.223-5, Pollution Prevention and Right-to-Know Information (May 2011) (E.O. 13423) (Applies to services performed on Federal facilities).

(vii) 52.223-15, Energy Efficiency in Energy-Consuming Products (Dec 2007) (42 U.S.C. 8259b) (Unless exempt pursuant to 23.204, applies to contracts when energy-consuming products listed in the ENERGY STAR® Program or Federal Energy Management Program (FEMP) will be—

(A) Delivered;

(B) Acquired by the Contractor for use in performing services at a Federally-controlled facility;

(C) Furnished by the Contractor for use by the Government; or

(D) Specified in the design of a building or work, or incorporated during its construction, renovation, or maintenance.)

(viii) 52.225-1, Buy American Act--Supplies (Feb 2009) (41 U.S.C. 10a-10d) (Applies to contracts for supplies, and to contracts for services involving the furnishing of supplies, for use within the United States or its outlying areas, if the value of the supply contract or supply portion of a service contract exceeds the micro-purchase threshold and the acquisition—

(A) Is set aside for small business concerns; or

(B) Cannot be set aside for small business concerns (see 19.502-2), and does not exceed $25,000.)

(ix) 52.232-33, Payment by Electronic Funds Transfer-- Central Contractor Registration (Oct 2003). (Applies when the payment will be made by electronic funds transfer (EFT) and the payment office uses the Central Contractor Registration (CCR) database as its source of EFT information.)

(x) 52.232-34, Payment by Electronic Funds Transfer—Other than Central Contractor Registration (May 1999). (Applies when the payment will be made by EFT and the payment office does not use the CCR database as its source of EFT information.)

(xi) 52.247-64 Preference for Privately Owned U.S.-Flag Commercial Vessels (Feb 2006) (46 U.S.C. App. 1241). (Applies to supplies transported by ocean vessels (except for the types of subcontracts listed at 47.504(d).)

(2) Listed below are additional clauses that may apply:

(i) 52.209-6, Protecting the Government's Interest When Subcontracting with Contractors Debarred, Suspended, or Proposed for Debarment (Dec 2010) (Applies to contracts over $30,000). (Not applicable to subcontracts for the acquisition of commercially available off-the-shelf items).

(ii) 52.211-17, Delivery of Excess Quantities (Sep 1989) (Applies to fixed-price supplies).

(iii) 52.226-6, Promoting Excess Food Donation to Nonprofit Organizations. (Mar 2009) (Pub. L. 110 247) (Applies to contracts greater than $25,000 that provide for the provision, the service, or the sale of food in the United states.)

(iv) 52.247-29, F.o.b. Origin (Feb 2006) (Applies to supplies if delivery is f.o.b. origin).

(v) 52.247-34, F.o.b. Destination (Nov 1991) (Applies to supplies if delivery is f.o.b. destination).

(c) *FAR 52.252-2, Clauses Incorporated by Reference (Feb 1998).* This contract incorporates one or more clauses by
reference, with the same force and effect as if they were given in full text. Upon request, the Contracting Officer will make their full text available. Also, the full text of a clause may be accessed electronically at this/these address(es):

http://farsite.hill.af.mil/
http://www.acq.osd.mil/dpap/dars/dfars/

(d) *Inspection/Acceptance.* See Section 1 of Purchase Order.

(e) *Excusable delays.* The Contractor shall be liable for default unless nonperformance is caused by an occurrence beyond the reasonable control of the Contractor and without its fault or negligence, such as acts of God or the public enemy, acts of the Government in either its sovereign or contractual capacity, fires, floods, epidemics, quarantine restrictions, strikes, unusually severe weather, and delays of common carriers. The Contractor shall notify the Contracting Officer in writing as soon as it is reasonably possible after the commencement of any excusable delay, setting forth the full particulars in connection therewith, shall remedy such occurrence with all reasonable dispatch, and shall promptly give written notice to the Contracting Officer of the cessation of such occurrence.

(f) *Termination for the Government's convenience.* The Government reserves the right to terminate this contract, or any part hereof, for its sole convenience. In the event of such termination, the Contractor shall immediately stop all work hereunder and shall immediately cause any and all of its suppliers and subcontractors to cease work. Subject to the terms of this contract, the Contractor shall be paid a percentage of the contract price reflecting the percentage of the work performed prior to the notice of termination, plus reasonable charges that the Contractor can demonstrate to the satisfaction of the Government, using its standard record keeping system, have resulted from the termination. The Contractor shall not be required to comply with the cost accounting standards or contract cost principles for this purpose. This paragraph does not give the Government any right to audit the Contractor's records. The Contractor shall not be paid for any work performed or costs incurred that reasonably could have been avoided.

(g) *Termination for cause.* The Government may terminate this contract, or any part hereof, for cause in the event of any default by the Contractor, or if the Contractor fails to comply with any contract terms and conditions, or fails to

provide the Government, upon request, with adequate assurances of future performance. In the event of termination for cause, the Government shall not be liable to the Contractor for any amount for supplies or services not accepted, and the Contractor shall be liable to the Government for any and all rights and remedies provided by law. If it is determined that the Government improperly terminated this contract for default, such termination shall be deemed a termination for convenience.

(End of Clause)

6. ATTACHMENTS

Attachment 1 Statement of Work (7-18-11)

DAPRA/TTO META Program Component Model Library

CMU-NREC Statement of Work

July 18, 2011

Overview

This Statement of Work (SOW) outlines Carnegie Mellon University, National Robotics Engineering Center's (CMU-NREC) tasks planned for supporting DARPA TTO's META program. Under this effort NREC will prepare, package, and deliver unmanned ground vehicle (UGV) cooling system models to DARPA, and will provide technical support if requested in addressing questions related to and modifications to the models. The models will be utilized by the performers of the META program. This effort will fulfill the need for a set of system and component models sufficiently detailed to exercise the META tools currently under development. The META program is at a stage when tool maturation and integration requires the use of such a set of models. This purchase is essential to the completion of the META program.

Work Tasks

Task 1: Select models

CMU-NREC will identify and extract the appropriate models from a complete set of models that currently exist for a field-proven experimental UGV (XV). Specific emphasis is placed on the various models and modeling functions that address the thermal management/cooling system of the XV.

CMU will extract and package the following:

- CAD models that capture the detailed geometry, dimensions, and mechanical interfaces. The original models are in SolidWorks format. XV's thermal management CAD model includes more than 700 part models.
- Thermal fluid-simulation models in KULI format. KULI is a one-dimensional thermal-fluid simulation software package with a block-diagram style GUI .For the XV program it was used to rapidly model candidate cooling topologies, simulate their performance and investigate the effects of system modifications while fine-tuning the design. XV's KULI model includes more than 600 part models.
- MATLAB-Simulink models and functions that were used to model XV heat rejection from various components and this data was fed into KULI for thermal-fluid (cooling system performance) simulation. The results from KULI were component and fluid temperatures, air and coolant flow rates and required cooling fan powers.
- Documents summarizing the XV thermal management system, cooling circuits, key components, and performance in Adobe pdf format.

Task 2: Prepare models for use

This task represents a significant portion of the overall effort. It is expected that the following activities will be undertaken:

- Clean-up and reduce models as necessary: In response to specific needs and requirements of DARPA, CMU will further prepare specific portions of the XV thermal management model for the META Program performers. For example, focus may be placed on the cooling circuit of the XV engine pack, cooling of major electronics associated with the drivetrain, etc.
- CMU will simplify the design tree of the thermal management system and generate a discretization of subassemblies that will ease the abstraction of the XV models and potentially allow for multi-scale studies to be performed. CMU will generate a description of the design tree and definitions for the subassemblies.
- Check for model consistency and applicability: CMU will work to ensure that the selected models and code are prepared in a way that allows for use by parties with no specific knowledge of the XV design to the highest degree possible. CMU will run the thermal models to ensure that they are working properly. CMU will utilize its own SolidWorks and MATLAB/Simulink licenses to run and verify the models. CMU has also requested a zero-fee reapplication of its KULI license.
- Develop documentation that defines the models, model structure, interfaces between models, and process to run the models. CMU will prepare all required documentation to understand the content of the models and process to run them.

CMU will work with DARPA to prepare the models and relevant documentation in the best possible form to support the needs of the META Program.

Task 3: Deliver models to DARPA

CMU will deliver the models and associated documentation to DARPA as soon as that material receives Operations Security (OPSEC) clearance by the U.S. Army's Tank Automotive Research, Development and Engineering Center (TARDEC).

CMU engineers will work closely with DARPA personnel throughout this effort. As part of the delivery, CMU will provide training on the content of the models and process to run relevant simulations and sensitivity studies.

Task 4: Provide post-delivery support

CMU will support DARPA in disseminating the models to the META program performers and will provide expertise to answer questions and clarify aspects of the design and simulation models as requested.

Deliverables

Useable models of the thermal management system of CMU's XV, including:

- SolidWorks CAD mechanical part and assembly files
- KULI thermal modeling component and system model files
- MATLAB-Simulink files supporting KULI simulation
- Document describing XV's thermal management system, major cooling circuits, and summary performance
- Document describing model details, file content, simulation running instructions, input/output, etc.

Schedule

Month 1: Tasks 1 and 2

Month 2: Tasks 2 and 3

Month 3: Task 4

AMENDMENT OF SOLICITATION/MODIFICATION OF CONTRACT

1. CONTRACT ID CODE: J
PAGE OF PAGES: 1 | 2

2. AMENDMENT/MODIFICATION NO.	3. EFFECTIVE DATE	4. REQUISITION/PURCHASE REQ. NO.	5. PROJECT NO. (If applicable)
P00001	03-Jan-2012	7925/00	

6. ISSUED BY CODE HR0011

DARPA
CMO
ATTN: CHRISTOPHER GLISTA
3701 N. FAIRFAX DR.
ARLINGTON VA 22203

7. ADMINISTERED BY (If other than item 6) CODE

See Item 6

8. NAME AND ADDRESS OF CONTRACTOR (No., Street, County, State and Zip Code)
CARNEGIE MELLON UNIVERSITY
5000 FORBES AVE
PITTSBURGH PA 15213-3815

9A. AMENDMENT OF SOLICITATION NO.

9B. DATED (SEE ITEM 11)

X 10A. MOD. OF CONTRACT/ORDER NO. HR0011-11-P-0016

X 10B. DATED (SEE ITEM 13) 02-Sep-2011

CODE 97668 FACILITY CODE

11. THIS ITEM ONLY APPLIES TO AMENDMENTS OF SOLICITATIONS

☐ The above numbered solicitation is amended as set forth in Item 14. The hour and date specified for receipt of Offer ☐ is extended, ☐ is not extended.

Offer must acknowledge receipt of this amendment prior to the hour and date specified in the solicitation or as amended by one of the following methods: (a) By completing Items 8 and 15, and returning ______ copies of the amendment; (b) By acknowledging receipt of this amendment on each copy of the offer submitted; or (c) By separate letter or telegram which includes a reference to the solicitation and amendment numbers. FAILURE OF YOUR ACKNOWLEDGMENT TO BE RECEIVED AT THE PLACE DESIGNATED FOR THE RECEIPT OF OFFERS PRIOR TO THE HOUR AND DATE SPECIFIED MAY RESULT IN REJECTION OF YOUR OFFER. If by virtue of this amendment you desire to change an offer already submitted, such change may be made by telegram or letter, provided each telegram or letter makes reference to the solicitation and this amendment, and is received prior to the opening hour and date specified.

12. ACCOUNTING AND APPROPRIATION DATA (If required)

13. THIS ITEM APPLIES ONLY TO MODIFICATIONS OF CONTRACTS/ORDERS.
IT MODIFIES THE CONTRACT/ORDER NO. AS DESCRIBED IN ITEM 14.

A. THIS CHANGE ORDER IS ISSUED PURSUANT TO: (Specify authority) THE CHANGES SET FORTH IN ITEM 14 ARE MADE IN THE CONTRACT ORDER NO. IN ITEM 10A.

B. THE ABOVE NUMBERED CONTRACT/ORDER IS MODIFIED TO REFLECT THE ADMINISTRATIVE CHANGES (such as changes in paying office, appropriation date, etc.) SET FORTH IN ITEM 14, PURSUANT TO THE AUTHORITY OF FAR 43.103(B).

X C. THIS SUPPLEMENTAL AGREEMENT IS ENTERED INTO PURSUANT TO AUTHORITY OF:
By mutual agreement of the Parties.

D. OTHER (Specify type of modification and authority)

E. IMPORTANT: Contractor ☐ is not, ☒ is required to sign this document and return 1 copies to the issuing office.

14. DESCRIPTION OF AMENDMENT/MODIFICATION (Organized by UCF section headings, including solicitation/contract subject matter where feasible.)
Modification Control Number: cglista12335

See page 2.

Except as provided herein, all terms and conditions of the document referenced in Item 9A or 10A, as heretofore changed, remains unchanged and in full force and effect.

15A. NAME AND TITLE OF SIGNER (Type or print)
Susan Burkett
Associate Vice President

16A. NAME AND TITLE OF CONTRACTING OFFICER (Type or print)
CHRISTOPHER L. GLISTA
TEL: (571) 218-4405 EMAIL: christopher.glista@darpa.mil

15B. CONTRACTOR/OFFEROR
(Signature of person authorized to sign)

15C. DATE SIGNED
1/12/12

16B. UNITED STATES OF AMERICA
BY
(Signature of Contracting Officer)

16C. DATE SIGNED

SECTION SF 30 BLOCK 14 CONTINUATION PAGE

SUMMARY OF CHANGES

SECTION 18-23 - ADDITIONS TO DD FORM 1155

The following Delivery Schedule item for CLIN 0001 has been changed from:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 02-SEP-2011 TO 03-JAN-2012	N/A	DARPA PAUL EREMENKO ATTN: TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 571-218-4889 FOB: Destination	HR0011

To:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 02-SEP-2011 TO 10-FEB-2012	N/A	DARPA PAUL EREMENKO ATTN: TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 571-218-4889 FOB: Destination	HR0011

The following have been modified:

2. PERFORMANCE

The term of the Purchase Order shall be from September 2, 2011 through February 10, 2012.

(End of Summary of Changes)

AMENDMENT OF SOLICITATION/MODIFICATION OF CONTRACT

1. CONTRACT ID CODE: J
PAGE OF PAGES: 1 | 2

2. AMENDMENT/MODIFICATION NO.	3. EFFECTIVE DATE	4. REQUISITION/PURCHASE REQ. NO.	5. PROJECT NO. (If applicable)
P00002	14-Feb-12	7925/00	

6. ISSUED BY CODE HR0011

DARPA
CMO
ATTN: CHRISTOPHER GLISTA
3701 N. FAIRFAX DR.
ARLINGTON VA 22203

7. ADMINISTERED BY (If other than item 6) CODE

See Item 6

8. NAME AND ADDRESS OF CONTRACTOR (No., Street, County, State and Zip Code)
CARNEGIE MELLON UNIVERSITY
5000 FORBES AVE
PITTSBURGH PA 15213-3815

9A. AMENDMENT OF SOLICITATION NO.

9B. DATED (SEE ITEM 11)

X 10A. MOD. OF CONTRACT/ORDER NO.
HR0011-11-P-0016

X 10B. DATED (SEE ITEM 13)
02-Sep-2011

CODE 97668 FACILITY CODE

11. THIS ITEM ONLY APPLIES TO AMENDMENTS OF SOLICITATIONS

☐ The above numbered solicitation is amended as set forth in Item 14. The hour and date specified for receipt of Offer ☐ is extended, ☐ is not extended.

Offer must acknowledge receipt of this amendment prior to the hour and date specified in the solicitation or as amended by one of the following methods:
(a) By completing Items 8 and 15, and returning ______ copies of the amendment; (b) By acknowledging receipt of this amendment on each copy of the offer submitted; or (c) By separate letter or telegram which includes a reference to the solicitation and amendment numbers. FAILURE OF YOUR ACKNOWLEDGMENT TO BE RECEIVED AT THE PLACE DESIGNATED FOR THE RECEIPT OF OFFERS PRIOR TO THE HOUR AND DATE SPECIFIED MAY RESULT IN REJECTION OF YOUR OFFER. If by virtue of this amendment you desire to change an offer already submitted, such change may be made by telegram or letter, provided each telegram or letter makes reference to the solicitation and this amendment, and is received prior to the opening hour and date specified.

12. ACCOUNTING AND APPROPRIATION DATA (If required)

13. THIS ITEM APPLIES ONLY TO MODIFICATIONS OF CONTRACTS/ORDERS
IT MODIFIES THE CONTRACT/ORDER NO. AS DESCRIBED IN ITEM 14.

A. THIS CHANGE ORDER IS ISSUED PURSUANT TO: (Specify authority) THE CHANGES SET FORTH IN ITEM 14 ARE MADE IN THE CONTRACT ORDER NO. IN ITEM 10A.

B. THE ABOVE NUMBERED CONTRACT/ORDER IS MODIFIED TO REFLECT THE ADMINISTRATIVE CHANGES (such as changes in paying office, appropriation date, etc.) SET FORTH IN ITEM 14, PURSUANT TO THE AUTHORITY OF FAR 43.103(B).

X C. THIS SUPPLEMENTAL AGREEMENT IS ENTERED INTO PURSUANT TO AUTHORITY OF:
By Mutual Agreement of the Parties

D. OTHER (Specify type of modification and authority)

E. IMPORTANT: Contractor ☐ is not, ☒ is required to sign this document and return 1 copies to the issuing office.

14. DESCRIPTION OF AMENDMENT/MODIFICATION (Organized by UCF section headings, including solicitation/contract subject matter where feasible.)
Modification Control Number: [redacted]

The purpose of this modification is to extend the period of performance from 10-Feb-12 to 12-Mar-12, at no additional cost to the Government.

See Summary of Changes for details.

Except as modified above, all terms and conditions of HR0011-11-P-0016 remain unchanged and in effect.

Except as provided herein, all terms a[redacted]m 9A or 10A, as heretofore changed, remains unchanged and in full force and effect.

15A. NAME AND TITLE OF [redacted]

16A. NAME AND TITLE OF CONTRACTING OFFICER (Type or print)
Chris L. Glista
TEL: (571) 218-4405 EMAIL: Christopher.Glista@darpa.mil

[redacted]

15C. DATE SIGNED
2/13/12

16[redacted]
(Signature of Contracting Officer)

16C. DATE SIGNED
2/14/12

SECTION SF 30 BLOCK 14 CONTINUATION PAGE

SECTION 18-23 - ADDITIONS TO DD FORM 1155

SUMMARY OF CHANGES

SECTION 18-23 - ADDITIONS TO DD FORM 1155

The following Delivery Schedule item for CLIN 0001 has been changed from:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 02-SEP-2011 TO 10-FEB-2012	N/A	DARPA PAUL EREMENKO ATTN: TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 571-218-4889 FOB: Destination	HR0011

To:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 02-SEP-2011 TO 12-MAR-2012	N/A	DARPA PAUL EREMENKO ATTN: TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 571-218-4889 FOB: Destination	HR0011

The following have been modified:

2. PERFORMANCE

The term of the Purchase Order shall be from September 2, 2011 through March 12, 2012.

(End of Summary of Changes)

AMENDMENT OF SOLICITATION/MODIFICATION OF CONTRACT

1. CONTRACT ID CODE: J

PAGE 1 OF 6 PAGES

2. AMENDMENT/MODIFICATION NO.: P00003

3. EFFECTIVE DATE: 19-Mar-12

4. REQUISITION/PURCHASE REQ. NO.: SEE SCHEDULE

5. PROJECT NO. (If applicable)

6. ISSUED BY — CODE: HR0011

DARPA
CMO
ATTN: CHRISTOPHER GLISTA
3701 N. FAIRFAX DR.
ARLINGTON VA 22203

7. ADMINISTERED BY (If other than item 6) — CODE

See Item 6

8. NAME AND ADDRESS OF CONTRACTOR (No., Street, County, State and Zip Code)

CARNEGIE MELLON UNIVERSITY
5000 FORBES AVE
PITTSBURGH PA 15213-3815

CODE: 97668 — FACILITY CODE

9A. AMENDMENT OF SOLICITATION NO.

9B. DATED (SEE ITEM 11)

X 10A. MOD. OF CONTRACT/ORDER NO.: HR0011-11-P-0016

X 10B. DATED (SEE ITEM 13): 02-Sep-2011

11. THIS ITEM ONLY APPLIES TO AMENDMENTS OF SOLICITATIONS

☐ The above numbered solicitation is amended as set forth in Item 14. The hour and date specified for receipt of Offer ☐ is extended, ☐ is not extended.

Offer must acknowledge receipt of this amendment prior to the hour and date specified in the solicitation or as amended by one of the following methods: (a) By completing Items 8 and 15, and returning ______ copies of the amendment; (b) By acknowledging receipt of this amendment on each copy of the offer submitted; or (c) By separate letter or telegram which includes a reference to the solicitation and amendment numbers. FAILURE OF YOUR ACKNOWLEDGMENT TO BE RECEIVED AT THE PLACE DESIGNATED FOR THE RECEIPT OF OFFERS PRIOR TO THE HOUR AND DATE SPECIFIED MAY RESULT IN REJECTION OF YOUR OFFER. If by virtue of this amendment you desire to change an offer already submitted, such change may be made by telegram or letter, provided each telegram or letter makes reference to the solicitation and this amendment, and is received prior to the opening hour and date specified.

12. ACCOUNTING AND APPROPRIATION DATA (If required)

See Schedule

13. THIS ITEM APPLIES ONLY TO MODIFICATIONS OF CONTRACTS/ORDERS.
IT MODIFIES THE CONTRACT/ORDER NO. AS DESCRIBED IN ITEM 14.

A. THIS CHANGE ORDER IS ISSUED PURSUANT TO: (Specify authority) THE CHANGES SET FORTH IN ITEM 14 ARE MADE IN THE CONTRACT ORDER NO. IN ITEM 10A.

B. THE ABOVE NUMBERED CONTRACT/ORDER IS MODIFIED TO REFLECT THE ADMINISTRATIVE CHANGES (such as changes in paying office, appropriation date, etc.) SET FORTH IN ITEM 14, PURSUANT TO THE AUTHORITY OF FAR 43.103(B).

X C. THIS SUPPLEMENTAL AGREEMENT IS ENTERED INTO PURSUANT TO AUTHORITY OF:
By Mutual Agreement of the Parties

D. OTHER (Specify type of modification and authority)

E. IMPORTANT: Contractor ☐ is not, ☒ is required to sign this document and return 1 copies to the issuing office.

14. DESCRIPTION OF AMENDMENT/MODIFICATION (Organized by UCF section headings, including solicitation/contract subject matter where feasible.)
Modification Control Number: (b)(6) [redacted]

See Summary of Changes.

Except as provided herein, all t (b)(4); (b)(6) [redacted] ment referenced in Item 9A or 10A, as heretofore changed, remains unchanged and in full force and effect.

15A. NAME AND TITLE O [redacted]

16A. NAME AND TITLE OF CONTRACTING OFFICER (Type or print)
Chris L. Glista
TEL: (571) 218-4405 — EMAIL: Christopher.Glista@darpa.mil

(b)(4); (b)(6) [redacted]

15C. DATE SIGNED: 3/16/12

16B. U (b)(6) [redacted]
BY [redacted]
(Signature of Contracting Officer)

16C. DATE SIGNED: 3/19/12

SECTION SF 30 BLOCK 14 CONTINUATION PAGE

The following items are applicable to this modification:

SECTION 18-23 - ADDITIONS TO DD FORM 1155

SUMMARY OF CHANGES

SECTION 18-23 - ADDITIONS TO DD FORM 1155

The total cost of this contract was increased by $20,529.00 from $94,999.00 to $115,528.00.

CLIN 0001

The CLIN extended description has changed

From:

'The Contractor shall support DARPA/TTO's META program in accordance with the Statement of Work - Attachment 1, dated July 18, 2011.'

To:

'The Contractor shall support DARPA/TTO's META program in accordance with the Statement of Work - Attachment 1.'

The unit price amount has decreased by $49,827.00 from $94,999.00 to $45,172.00.
The total cost of this line item has decreased by $49,827.00 from $94,999.00 to $45,172.00.

CLIN 0002 is added as follows:

ITEM NO.	SUPPLIES/SERVICES	QUANTITY	UNIT	UNIT PRICE	AMOUNT
0002		1	Lot	$33,000.00	$33,000.00
	META Component Model Library FFP In accordance with the Statement of Work - Attachment 1, the Contractor shall deliver the following: - Monthly summary progress update covering project activity and CAD/structural models. 03/31/2012 - Monthly summary progress update covering project activity and Analytical/simulation models. 04/30/2012 FOB: Destination				
				NET AMT	$33,000.00

SUBCLIN 000201 is added as follows:

ITEM NO.	SUPPLIES/SERVICES	QUANTITY	UNIT	UNIT PRICE	AMOUNT
000201					$0.00
	Funding for CLIN 0002 FFP AO 7925/00 FOB: Destination AO No. 7925/00				
				NET AMT	$0.00
	ACRN AA CIN: 000000000000000000000000000000				$33,000.00

CLIN 0003 is added as follows:

ITEM NO.	SUPPLIES/SERVICES	QUANTITY	UNIT	UNIT PRICE	AMOUNT
0003		1	Lot	$37,356.00	$37,356.00
	META Component Model Library FFP In accordance with the Statement of Work - Attachment 1, the Contractor shall deliver the following: - Monthly summary progress update covering project activity, the Solid Works CAD mechanical part and assembly, and Structural, thermal, and/or fluid modeling component and system model files. 05/31/2012 - Files supporting simulations. 05/31/2012 - Final report including description of XV's specified subsystems, model details, file content, simulation running instructions, input/output, etc., and summary of overall project performance. 06/15/2012 FOB: Destination				
				NET AMT	$37,356.00

SUBCLIN 000301 is added as follows:

ITEM NO.	SUPPLIES/SERVICES	QUANTITY	UNIT	UNIT PRICE	AMOUNT
000301					$0.00
	Funding for CLIN 0003 FFP AO 7925/00 FOB: Destination AO No. 7925/00				
				NET AMT	$0.00
	ACRN AA CIN: 000000000000000000000000000000				$16,827.00

SUBCLIN 000302 is added as follows:

ITEM NO.	SUPPLIES/SERVICES	QUANTITY	UNIT	UNIT PRICE	AMOUNT
000302	Funding for CLIN 0003 FFP AO 7925/01 FOB: Destination AO No. 7925/01				$0.00
				NET AMT	$0.00
	ACRN AB CIN: 000000000000000000000000000000				$20,529.00

The following Delivery Schedule item for CLIN 0001 has been changed from:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 02-SEP-2011 TO 12-MAR-2012	N/A	DARPA PAUL EREMENKO ATTN: TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 571-218-4889 FOB: Destination	HR0011

To:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 02-SEP-2011 TO 12-MAR-2012	N/A	DARPA LTC NATHAN WIEDENMAN, PHD TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 703-248-1532 FOB: Destination	HR0011

The following Delivery Schedule item has been added to CLIN 0002:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 19-MAR-2012 TO 30-APR-2012	N/A	DARPA LTC NATHAN WIEDENMAN, PHD TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 703-248-1532 FOB: Destination	HR0011

The following Delivery Schedule item has been added to CLIN 0003:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 19-MAR-2012 TO 15-JUN-2012	N/A	DARPA LTC NATHAN WIEDENMAN, PHD TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 703-248-1532 FOB: Destination	HR0011

Accounting and Appropriation

Summary for the Payment Office

As a result of this modification, the total funded amount for this document was increased by $20,529.00 from $94,999.00 to $115,528.00.

SUBCLIN 000101:

AA: 9710400 1320 7925 P1M30 2525 DPAC 1 5362 S12136 62303E (CIN 000000000000000000000000000000) was decreased by $49,827.00 from $94,999.00 to $45,172.00

SUBCLIN 000201:
Funding on SUBCLIN 000201 is initiated as follows:

ACRN: AA
CIN: 000000000000000000000000000000
Acctng Data: 9710400 1320 7925 P1M30 2525 DPAC 1 5362 S12136 62303E
Increase: $33,000.00
Total: $33,000.00

SUBCLIN 000301:
Funding on SUBCLIN 000301 is initiated as follows:

ACRN: AA
CIN: 000000000000000000000000000000
Acctng Data: 9710400 1320 7925 P1M30 2525 DPAC 1 5362 S12136 62303E
Increase: $16,827.00
Total: $16,827.00

SUBCLIN 000302:
Funding on SUBCLIN 000302 is initiated as follows:

ACRN: AB
CIN: 000000000000000000000000000000
Acctng Data: 9720400 1320 7925 P2M30 2525 DPAC 2 5202 S12136 62303E
Increase: $20,529.00
Total: $20,529.00

The following have been **modified**:

2. PERFORMANCE

The term of the Purchase Order shall be from September 2, 2011 through **June 15, 2012**.

3. PURCHASE ORDER ADMINISTRATIVE DATA

(c) For each invoice/cost voucher submitted for payment, the contractor shall also e-mail the WAWF automated invoice notice directly to the following points of contact:

Name	E-mail	Phone	Role
Chris Glista	christopher.glista@darpa.mil	(571) 218-4405	Contracting Officer
Nathan Wiedenman	**nathan.wiedenman@darpa.mil**	**(703) 248-1532**	**META Program Manager**

6. ATTACHMENTS

Attachment 1 – Statement of Work **(3-12-12)**

(End of Summary of Changes)

DAPRA/TTO META Program Component Model Library
CMU-NREC Statement of Work
Revised March 12, 2012

Overview

This Statement of Work (SOW) outlines Carnegie Mellon University, National Robotics Engineering Center's (CMU-NREC) tasks planned for supporting DARPA TTO's META program. Under this effort NREC will prepare, package, and deliver unmanned ground vehicle (UGV) cooling system models to DARPA, and will provide technical support if requested in addressing questions related to and modifications to the models. The models will be utilized by the performers of the META program. This effort will fulfill the need for a set of system and component models sufficiently detailed to exercise the META tools currently under development. The META program is at a stage when tool maturation and integration requires the use of such a set of models. This purchase is essential to the completion of the META program.

Work Tasks

Task 1: Select models

CMU-NREC will identify and extract the appropriate models from a complete set of models that currently exist for a field-proven experimental UGV (XV). Specific emphasis is placed on the various models and modeling functions that address the thermal management/cooling system of the XV.

CMU will extract and package the following:

- CAD models that capture the detailed geometry, dimensions, and mechanical interfaces. The original models are in SolidWorks format. XV's thermal management CAD model includes more than 700 part models.
- Thermal fluid-simulation models in KULI format. KULI is a one-dimensional thermal-fluid simulation software package with a block-diagram style GUI .For the XV program it was used to rapidly model candidate cooling topologies, simulate their performance and investigate the effects of system modifications while fine-tuning the design. XV's KULI model includes more than 600 part models.
- MATLAB-Simulink models and functions that were used to model XV heat rejection from various components and this data was fed into KULI for thermal-fluid (cooling system performance) simulation. The results from KULI were component and fluid temperatures, air and coolant flow rates and required cooling fan powers.
- Documents summarizing the XV thermal management system, cooling circuits, key components, and performance in Adobe pdf format.

Task 2: Prepare models for use

This task represents a significant portion of the overall effort. It is expected that the following activities will be undertaken:

- Clean-up and reduce models as necessary: In response to specific needs and requirements of DARPA, CMU will further prepare specific portions of the XV thermal management model for the META Program performers. For example, focus may be placed on the cooling circuit of the XV engine pack, cooling of major electronics associated with the drivetrain, etc.
- CMU will simplify the design tree of the thermal management system and generate a discretization of subassemblies that will ease the abstraction of the XV models and potentially allow for multi-scale studies to be performed. CMU will generate a description of the design tree and definitions for the subassemblies.
- Check for model consistency and applicability: CMU will work to ensure that the selected models and code are prepared in a way that allows for use by parties with no specific knowledge of the XV design to the highest degree possible. CMU will run the thermal models to ensure that they are working properly. CMU will utilize its own SolidWorks and MATLAB/Simulink licenses to run and verify the models. CMU has also requested a zero-fee reapplication of its KULI license.
- Develop documentation that defines the models, model structure, interfaces between models, and process to run the models. CMU will prepare all required documentation to understand the content of the models and process to run them.

CMU will work with DARPA to prepare the models and relevant documentation in the best possible form to support the needs of the META Program.

Task 3: Deliver models to DARPA

CMU will deliver the models and associated documentation to DARPA as soon as that material receives Operations Security (OPSEC) clearance by the U.S. Army's Tank Automotive Research, Development and Engineering Center (TARDEC).

CMU engineers will work closely with DARPA personnel throughout this effort. As part of the delivery, CMU will provide training on the content of the models and process to run relevant simulations and sensitivity studies.

Task 4: Provide post-delivery support

CMU will support DARPA in disseminating the models to the META program performers and will provide expertise to answer questions and clarify aspects of the design and simulation models as requested.

Task 5: Models of chassis and structural subsystems

CMU-NREC will identify and extract the appropriate models from a complete set of models that currently exist for a field-proven experimental Unmanned Ground Vehicle (XV). Specific emphasis is placed on the various models and modeling functions that address the chassis and structural subsystems of the XV.

CMU will extract and package the following:

- CAD models that capture the detailed geometry, dimensions, and mechanical interfaces. The original models are in SolidWorks format.
- Structural, thermal, and/or fluid simulation models for the chassis and structural subsystems.
- MATLAB-Simulink models and functions that were used to support domain-specific models.
- Documents summarizing the XV mobility system, key components, and performance in Adobe pdf format.
- Clean-up and reduce models as necessary.
- CMU will simplify the design tree of the chassis and structural subsystems and generate a discretization of subassemblies that will ease the abstraction of the XV models and potentially allow for multi-scale studies to be performed. CMU will generate a description of the design tree and definitions for the subassemblies.
- Check for model consistency and applicability: CMU will work to ensure that the selected models and code are prepared in a way that allows for use by parties with no specific knowledge of the XV design to the highest degree possible. CMU will run the models to ensure that they are working properly. CMU will utilize its own SolidWorks and MATLAB/Simulink licenses to run and verify the models.
- Develop documentation that defines the models, model structure, interfaces between models, and process to run the models. CMU will prepare all required documentation to understand the content of the models and process to run them.

CMU engineers will work closely with DARPA personnel throughout this effort. As part of the delivery, CMU will provide instrcutions on the content of the models and process to run relevant simulations and sensitivity studies.

Task 6: Consult to DARPA C2M2L efforts

For both C2M2L-1 and C2M2L-2 TAs 1&2, CMU will assist in a consulting role. Specific needs will be with respect to component and context models: what should these consist of and in what format(s)? CMU will provide a knowledgeable point of contact who is responsive to queries from ongoing modeling efforts in the Adaptive Vehicle Make portfolio. This individual should plan to attend the DARPA AVM PI meeting at Purdue University, March 20-22 2012, potentially hosting a workshop on these topics.

Deliverables

Useable models of the thermal management system of CMU's XV, including:

- SolidWorks CAD mechanical part and assembly files
- KULI thermal modeling component and system model files
- MATLAB-Simulink files supporting KULI simulation
- Document describing XV's thermal management system, major cooling circuits, and summary performance
- Document describing model details, file content, simulation running instructions, input/output, etc.

Task 5 & 6 Milestones and Deliverables:

- CAD/structural models extracted – 02/29/2012
- Analytical/simulation models extracted – 03/15/2012
- CAD/structural models cleaned up reduced – 03/31/2012
- Analytical/simulation models cleaned up and reduced – 04/15/2012
- All models reduced and re-packaged – 05/15/2012
- SolidWorks CAD mechanical part and assembly files – 05/31/2012
- Structural, thermal, and/or fluid modeling component and system model files – 05/31/2012
- MATLAB-Simulink files supporting simulations – 05/31/2012
- Document describing XV's specified subsystems, and summary performance – 06/15/2012
- Document describing model details, file content, simulation running instructions, input/output, etc. – 06/15/2012

AMENDMENT OF SOLICITATION/MODIFICATION OF CONTRACT

1. CONTRACT ID CODE	PAGE OF PAGES
J	1 / 3

2. AMENDMENT/MODIFICATION NO.	3. EFFECTIVE DATE	4. REQUISITION/PURCHASE REQ. NO.	5. PROJECT NO.(If applicable)
P00004	10-Aug-2012	SEE SCHEDULE	

6. ISSUED BY CODE HR0011	7. ADMINISTERED BY (If other than item 6) CODE HR0011
DARPA CMO ATTN: CHRISTOPHER GLISTA 675 N. RANDOLPH STREET ARLINGTON VA 22203-2114	DARPA CMO ATTN: CHRISTOPHER GLISTA 3701 N. FAIRFAX DR. ARLINGTON VA 22203

8. NAME AND ADDRESS OF CONTRACTOR (No., Street, County, State and Zip Code)
CARNEGIE MELLON UNIVERSITY
5000 FORBES AVE
PITTSBURGH PA 15213-3815

CODE 97668 FACILITY CODE

	9A. AMENDMENT OF SOLICITATION NO.
	9B. DATED (SEE ITEM 11)
X	10A. MOD. OF CONTRACT/ORDER NO. HR0011-11-P-0016
X	10B. DATED (SEE ITEM 13) 02-Sep-2011

11. THIS ITEM ONLY APPLIES TO AMENDMENTS OF SOLICITATIONS

☐ The above numbered solicitation is amended as set forth in Item 14. The hour and date specified for receipt of Offer ☐ is extended, ☐ is not extended.

Offer must acknowledge receipt of this amendment prior to the hour and date specified in the solicitation or as amended by one of the following methods: (a) By completing Items 8 and 15, and returning ______ copies of the amendment; (b) By acknowledging receipt of this amendment on each copy of the offer submitted; or (c) By separate letter or telegram which includes a reference to the solicitation and amendment numbers. FAILURE OF YOUR ACKNOWLEDGMENT TO BE RECEIVED AT THE PLACE DESIGNATED FOR THE RECEIPT OF OFFERS PRIOR TO THE HOUR AND DATE SPECIFIED MAY RESULT IN REJECTION OF YOUR OFFER. If by virtue of this amendment you desire to change an offer already submitted, such change may be made by telegram or letter, provided each telegram or letter makes reference to the solicitation and this amendment, and is received prior to the opening hour and date specified.

12. ACCOUNTING AND APPROPRIATION DATA (If required)

13. THIS ITEM APPLIES ONLY TO MODIFICATIONS OF CONTRACTS/ORDERS.
IT MODIFIES THE CONTRACT/ORDER NO. AS DESCRIBED IN ITEM 14.

	A. THIS CHANGE ORDER IS ISSUED PURSUANT TO: (Specify authority) THE CHANGES SET FORTH IN ITEM 14 ARE MADE IN THE CONTRACT ORDER NO. IN ITEM 10A.
	B. THE ABOVE NUMBERED CONTRACT/ORDER IS MODIFIED TO REFLECT THE ADMINISTRATIVE CHANGES (such as changes in paying office, appropriation date, etc.) SET FORTH IN ITEM 14, PURSUANT TO THE AUTHORITY OF FAR 43.103(B).
X	C. THIS SUPPLEMENTAL AGREEMENT IS ENTERED INTO PURSUANT TO AUTHORITY OF: By Mutual Agreement of the Parties.
	D. OTHER (Specify type of modification and authority)

E. IMPORTANT: Contractor ☐ is not, ☒ is required to sign this document and return 1 copies to the issuing office.

14. DESCRIPTION OF AMENDMENT/MODIFICATION (Organized by UCF section headings, including solicitation/contract subject matter where feasible.)
Modification Control Number: cglista121109

The purpose of this modification is to extend the period of performance from 6-Jun-12 to 11-Nov-12 at no additional cost to the Government. See page 2 for details.

Except as provided herein, all terms and conditions of the document referenced in Item 9A or 10A, as heretofore changed, remains unchanged and in full force and effect.

15A. NAME AND TITLE OF SIGNER (Type or print)
(b)(6) [redacted]

(b)(6) [redacted]
8/9/12

16A. NAME AND TITLE OF CONTRACTING OFFICER (Type or print)
CHRISTOPHER L. GLISTA
TEL: (571) 218-4405 EMAIL: christopher.glista@darpa.mil

16B. UNITED STATES OF AMERICA
BY ______________________
(Signature of Contracting Officer)

16C. DATE SIGNED

30-105-04

STANDARD FORM 30 (Rev. 10-83)
Prescribed by GSA
FAR (48 CFR) 53.243

SECTION SF 30 BLOCK 14 CONTINUATION PAGE

SUMMARY OF CHANGES

SECTION 18-23 - ADDITIONS TO DD FORM 1155

CLIN 0003

The CLIN 0003 extended description has changed from:

In accordance with the Statement of Work - Attachment 1, the Contractor shall deliver the following:
- Monthly summary progress update covering project activity, the Solid Works CAD mechanical part and assembly, and Structural, thermal, and/or fluid modeling component and system model files. 05/31/2012
- Files supporting simulations. 05/31/2012
- Final report including description of XV's specified subsystems, model details, file content, simulation running instructions, input/output, etc., and summary of overall project performance. 6-Jun-12

TO:

In accordance with the Statement of Work - Attachment 1, the Contractor shall deliver the following:
- Monthly summary progress update covering project activity, the Solid Works CAD mechanical part and assembly, and Structural, thermal, and/or fluid modeling component and system model files. 05/31/2012
- Files supporting simulations. 05/31/2012
- Final report including description of XV's specified subsystems, model details, file content, simulation running instructions, input/output, etc., and summary of overall project performance. **No later than 30-Nov-12.**

The following Delivery Schedule item for CLIN 0003 has been changed from:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 19-MAR-2012 TO 15-JUN-2012	N/A	DARPA LTC NATHAN WIEDENMAN, PHD TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 703-248-1532 FOB: Destination	HR0011

To:

DELIVERY DATE	QUANTITY	SHIP TO ADDRESS	UIC
POP 19-MAR-2012 TO 30-NOV-2012	N/A	DARPA LTC NATHAN WIEDENMAN, PHD TACTICAL TECHNOLOGY OFFICE 3701 NORTH FAIRFAX DRIVE ARLINGTON VA 22203-1714 703-248-1532 FOB: Destination	HR0011

The following have been modified:

2. PERFORMANCE

The term of the Purchase Order shall be from September 2, 2011 through November 30, 2012.

(End of Summary of Changes)

All other terms and conditions of purchase order HR0011-11-P-0016 shall remain in full force and effect, unless otherwise stated in Modification P00004 herein.

Agreement No.: HR0011-16-2-0021
Purchase Request No.: HR0011621740
Effective Date: April 29, 2016
DARPA's CFDA Number: 12.910
DODDAC: HR0011

Issued by: Defense Advanced Research Projects Agency (DARPA)
Contracts Management Office (CMO)
675 North Randolph Street
Arlington, VA 22203-2114
(Attn: Michael S. Mutty, 571-218-4588, michael.mutty@darpa.mil)

Recipient: Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213-3815
(Attn : (b)(6) [redacted]

Recipient Identification Numbers/Codes:

DUNS (b)(4) [redacted]
CAGE
TIN:

Total Cooperative Agreement Amount: $998,910.00

Accounting and Appropriation Data:

SUBCLIN	ACRN
0001/01	AA

FUND CITE

012199 097 0400 000 N 20162017 D 1320 DRVLDD 2016.MS-01.CORE.A DARPA 255

AMOUNT

$514,203.00

Payment Office Information:

DFAS IN VP DAI DARPA
8899 East 56th Street
Indianapolis, IN 46249-1500
DODAAC: HQ0685

[AWARD SUBJECT TO ELECTRONIC FUNDS TRANSFER (EFT) REQUIREMENT]

Authority: This Agreement is issued pursuant to the authority of 10 U.S.C. § 2358, as amended.

COOPERATIVE AGREEMENT SCHEDULE

1. Purpose: The purpose of this Cooperative Agreement is to fund research to the Recipient to carry out a public purpose of support or stimulation of the Defense Advanced Research Projects Agency (DARPA) Defense Sciences Office (DSO) Revolutionary Enhancement of Visibility by Exploiting Active Light-fields (REVEAL) Program. This effort shall be carried out generally as set forth in Exhibit B, Research Description Document, dated March 28, 2016.

2. Term: The term of this Cooperative Agreement commences on April 29, 2016 and continues through April 28, 2018.

(a) The Recipient shall make all requests for no-cost period of performance extensions, in writing, to the Administrative Agreements Officer, no later than 30 days prior to the end of the current period of performance. The Administrative Agreements Officer is delegated authority to grant such request, via modification to the Cooperative Agreement, after receiving approval from the Agreement Officer's Representative.

3. Terms and Conditions: This Cooperative Agreement is subject to the terms and conditions set forth in the attached Exhibit A, entitled "DARPA AGENCY SPECIFIC TERMS AND CONDITIONS," dated January 2016 and to any special terms and conditions in this Cooperative Agreement Schedule.

4. Agreement Officer's Representative: The Agreement Officer's Representative (AOR) representing the Government under this Cooperative Agreement is:

Dr. Ravindra Athale
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203
Phone#: 703-588-1916
E-mail: ravindra.athale@navy.mil
DoDAAC No.: N00014

5. DARPA Program Manager: The DARPA Program Manager (PM) representing the Government under this Cooperative Agreement is:

Defense Advanced Research Projects Agency
Defense Sciences Office (DSO)
ATTN.: Dr. Predrag Milojkovic
675 North Randolph Street
Arlington, VA 22203-2114
Phone#: 703-526-2845
E-mail: predrag.milojkovic@darpa.mil
DoDAAC No.: HR0011

6. Administrative Agreements Office: The Administrative Agreement Office (AAO) for this Cooperative Agreement is:

Office of Naval Research (ONRRO) Chicago
Chicago Regional Office
230 South Dearborn, Room 380
Chicago, IL 60605-1595
Phone#: 312-886-5423
E-mail: onr_chicago@navy.mil
DoDAAC#: N62880

7. Principal Investigator: The Principal Investigator shall be responsible for this effort.

Carnegie Mellon University
Attn: (b)(4); (b)(6) [redacted]
5000 Forbes Avenue
Pittsburgh, PA, 15213-3815
Phone#: (b)(4); (b)(6) [redacted]
E-mail:

The Recipient agrees to notify the AAO before changing the Principal Investigator.

8. Cooperative Agreement Funding: This Cooperative Agreement is incrementally funded in the amount of $514,203.00. The Government's obligation to make payments to the Recipient is limited to only those funds obligated by this Cooperative Agreement or by modification to this Cooperative Agreement. Subject to availability of funds and continued satisfactory progress on the Cooperative Agreement as determined by the Government, the Government agrees to provide funding according to the following schedule:

FY16: $484,707.00

The Cooperative Agreement Awardee shall notify the AAO in writing promptly whenever the total Cooperative Agreement amount is expected to exceed the needs of the Cooperative Agreement Awardee for the project period by more than 5% of the award. This notification shall not be required if an application for additional funding is submitted for a continuation award.

9. Payments: Payments will be made to the Recipient on a reimbursement basis and shall be made by electronic funds transfer in accordance with the account information provided to the System for Award Management.

10. Substantial Involvement: Substantial involvement is expected between the U. S. Government and the Recipient when carrying out the activity contemplated in this Cooperative Agreement. It will include the U. S. Government's (a) sharing responsibility for the management, control, direction, or performance of the project, and (b) retaining the right to intervene in the conduct or performance of the project. The substantial involvement will include the U.S. Government's direction of activities to develop the research protocols necessary to complete the work and the approval of analysis mechanisms. The U.S.

Government, DARPA, will participate in the presentation of research results, the analysis of data, and the selection of analysis methods.

11. List of Exhibits:

Exhibit A - DARPA Cooperative Agreement General Terms and Conditions (January 2016)
Exhibit B – Research Description Document (March 28, 2016)

FOR CARNEGIE MELLON UNIVERSITY

(b)(4); (b)(6) [redacted]

(Signature)

(b)(4); (b)(6) [redacted]

(Name, Title)

4-28-16

(Date)

FOR THE UNITED STATES OF AMERICA, DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

MUTTY.MICHAEL.S. (b)(6) [redacted] Digitally signed by MUTTY.MICHAEL (b)(6) [redacted] Date: 2016.04.29 07:27:30 -04'00'

MICHAEL S. MUTTY
Agreements Officer
Contracts Management Office

4/29/2016

(Date)

EXHIBIT A
JANUARY, 2016
DARPA AGENCY SPECIFIC TERMS AND CONDITIONS

This award is subject to the DoD Research and Development (R&D) general terms and conditions, which can be found at http://www.onr.navy.mil/Contracts-Grants/submit-proposal/grants-proposal/grants-terms-conditions.aspx under the header "DoD Research and Development General Terms and Conditions," dated October 2015, and are incorporated herein. The DARPA Agency Specific Terms and Conditions supplement the DoD Research and Development general terms and conditions. This document addresses agency-specific concerns in addition to the above referenced regulations. Award recipients (hereafter, recipient) are accountable for all applicable statutory and regulatory requirements that govern these awards, even if not specifically listed in this document or documents referenced herein.

ORDER OF PRECEDENCE

Any inconsistencies in the requirements of this award shall be resolved in the following order:
- Federal statutes
- Federal regulations
- 2 CFR part 200, as modified and supplemented by DoD's interim implementation found in 2 CFR part 1103
- Award-specific terms and conditions (DARPA Agency Specific terms and conditions)
- DoD Research and Development general terms and conditions

In case of disagreement with any requirements of this award, the recipient shall contact the Agreements Officer listed in the award document in order to resolve the issue. The recipient shall not assess any costs to the award or accept any payments until the issue is resolved.

1. Research Responsibility
2. Amendment of Award
3. Payments
4. Prior Approvals
5. Reports and Reports Distribution
6. Public Release or Dissemination of Information
7. Acknowledgment of Sponsorship
8. Intellectual Property Matters
9. Activities Abroad
10. Security
11. Research Involving Recombinant DNA Molecules
12. Restrictions on Printing
13. Prohibition on Awarding to Entities that Require Certain Internal Confidentiality Agreements

1) **Research Responsibility**:

a) The recipient has full responsibility for the conduct of the research activity supported by this award, in accordance with the recipient's proposal, and the terms and conditions specified in this award. Recipients are encouraged to suggest or propose to discontinue or modify unpromising lines of investigation or to explore interesting leads which may appear during the development of the research. However, they must consult the Agreement Officer's Representative (AOR) through the Administrative Agreements Officer (AAO) before significantly deviating from the objectives or overall program of the research originally proposed.

b) The recipient shall immediately notify the Agreements Officer of developments that have a significant impact on the award-supported activities. Also, notification shall be given in the case of problems, delays, or adverse conditions which materially impair the ability to meet the objectives of the award. This notification shall include a statement of the action taken or contemplated, and any assistance needed to resolve the situation.

2) **Amendment of Award:** The only method by which this award can be amended is by a formal, written amendment signed by either the Agreements Officer or the AAO. No other communications, whether oral or in writing, shall modify this award.

3) **Payments**:

a) Submitting Payments Through Wide Area Work Flow (WAWF): All payments shall be made by funds transfers to the bank account registered in the System for Award Management (SAM), http://www.sam.gov. The recipient agrees to maintain its registration in SAM, including information necessary to facilitate payment via Electronic Funds Transfer (EFT). Should a change in registry or other incident necessitate the payment to an account other than that maintained in SAM, it is the recipient's responsibility to notify the AAO and obtain a modification to this award reflecting the change. The Government shall not be held responsible for any misdirection or loss of payment which occurs as the result of a recipient's failure to maintain correct/current EFT information within its SAM registration.

1) Any request for advance payments must be approved by the AAO at the Administrative Office designated in the award document.

2) Wide Area Work Flow (WAWF) has been designated as the Department of Defense standard for electronic invoicing and payment. Electronic submission of payment requests requires the recipient to register in WAWF and have the appropriate CAGE code activated. The recipient's SAM Electronic Business Point of Contact (EBPOC) is responsible for activating the CAGE code in WAWF by calling 1-866-618-5988. Once the recipient's CAGE Code is activated, the SAM EBPOC will self-register in WAWF (https://wawf.eb.mil) and follow the instructions for a group administrator. The ONR Regional Offices will assist in this process. The ONR Regional Office is listed as the Administrative Office in the award document. Please call the ONR Regional Office with any questions regarding access to or use of WAWF.

4) **Prior Approvals:**

In addition to the prior approvals required by the DoD R&D general terms and conditions, prior written approval is required for the following actions:

- The subaward, transfer, or contracting out of any work under this award, unless described in the recipient's proposal and specifically approved and funded in the Award Schedule. The recipient's request for approval shall include the following supporting data:
  - (i) Basis for contractor selection;
  - (ii) Justification for lack of competition when competitive bids or offers are not obtained;
  - (iii) Basis for award cost or price, to include price or cost analysis performed by the recipient; and
  - (iv) Approval of the AOR.

5) **<u>Reports and Reports Distribution</u>**: Reports shall be furnished as specified below:

a) <u>Report Types</u>.

1) *Quarterly R&D Status Report* - This report, due 30 days after the reporting period, shall keep the Government informed of Recipient activity and progress toward accomplishment of Agreement objectives and advancement in state-of-the-art on the research and development including progress made toward achieving program performance goals. In addition, this report shall include the following business-related details: summarized details of the status of resources; accounting of expenditures for the period covered by the report in addition to cumulative expenditures to date; comparison of resource status with any payment and expenditure schedules or plans provided in the original proposal; explanation of any major deviations from those schedules; and discussion of proposed actions to address the deviations.

2) *Special Technical Report* - This report, due as required, shall document the results of a significant task, test, event or symposium.

3) *Final Technical Report* - This report, due 90 days after expiration or termination of the award, shall document the results of the complete effort. It shall contain brief information on each of the following:

a) A comparison of actual accomplishments with the goals and objectives established for the award, the findings of the investigator, or both.

b) Reasons why established goals were not met, if appropriate.

c) Other pertinent information.

4) *Final Financial Status Report* - This report, due 90 days after completion of the award, shall be submitted on a Standard Form 425 "Federal Financial Report (FFR)". The report shall be on a cash or accrual basis, depending on how the recipient's accounting records are normally kept.

5) *Report of Federal Cash Transactions [applicable only to advance payment awards]* – This report, due 15 days following the end of each quarter, shall be submitted on a Standard Form 425. The recipient shall provide forecasts of Federal cash requirements in the "Remarks" section of the report.

b) Report Distribution:

Addresses	Report Types [7.(a)]	Number of Copies
Agreement Officer's Representative Email: ravindra.athale@navy.mil	1, 2, 3, 4, 5	1
DARPA Program Manager Email: predrag.milojkovic@darpa.mil	1, 2, 3, 4, 5	1
Administrative Agreements Officer E-mail: onr_chicago@navy.mil	1, 3, 4, 5	1
DARPA Agreements Officer Email : ReportsDSO@darpa.mil	1, 3, 4, 5	1
DARPA/Research Support Center Email: Researchsupport@darpa.mil	3	1
Defense Technical Information Center ATTN: DTIC-O 8725 John J. Kingman Road Ft. Belvoir, VA 22060-6218 or Email: TR@dtic.mil	3	2 1

6) **Public Release or Dissemination of Information**

a) At this time, DARPA expects the work performed under this award to be fundamental research, and it is, therefore, not subject to publication restrictions. Papers resulting from unclassified contracted fundamental research are exempt from prepublication controls and requirements, pursuant to DoD Instruction 5230.27 dated October 6, 1987.

b) All papers resulting from this award will include the following distribution statement:

"Approved for public release; distribution is unlimited."

c) Should the character of the research change during award performance so that the research is no longer considered fundamental, the award will be modified to impose the restrictions on public release and dissemination of information that apply to those research efforts that are not considered fundamental research.

7) **Acknowledgment of Sponsorship:**

a) The recipient agrees that in the release of information relating to this award, such release shall include a statement to the effect that (1) the project or effort depicted was or is sponsored by the Defense Advanced Research Projects Agency, (2) the content of the information does not necessarily

reflect the position or the policy of the Government, and (3) no official endorsement should be inferred.

b) For the purpose of this article, information includes news releases, articles, manuscripts, brochures, advertisements, still and motion pictures, speeches, trade association proceedings, symposia, etc.

d) Nothing in the foregoing shall affect compliance with the requirements of the clause entitled "Security."

8) **Intellectual Property Matters**: Questions regarding intellectual property matters should be referred to Agreements Officer.

All patent reports (interim and final) shall be submitted using the i-Edison.gov reporting website (http://s-edison.info.nih.gov/iEdison). In the event the recipient is unable to submit reports through i-Edison, the recipient may utilize DD Form 882, Report of Inventions and Subcontracts, for submission of interim and final invention reports. The DD Form 882 and all invention disclosures shall be submitted to the AAO for proper disposition and forwarding to the Agreements Officer.

9) **Activities Abroad:** The recipient shall assure that project activities carried on outside the United States are coordinated as necessary with appropriate Government authorities and that appropriate licenses, permits, or approvals are obtained prior to undertaking proposed activities. The awarding agency does not assume responsibility for recipient compliance with the laws and regulations of the country in which the activities are to be conducted.

10) **Security:** The recipient may not be granted access to classified information under this award. If security restrictions should happen to apply to certain aspects of the proposed research, the recipient will be so informed. In the event that the scientific work under this award may need classification, or involve access to or storage of any classified data, the Government shall make its decision on the need to classify, or require such access or storage, within 30 days after receipt of written notice from the recipient. If the decision is affirmative, the Government shall invoke the clause in reference to the "Termination" proceedings in the DoD R&D general terms and conditions.

11) **Research Involving Recombinant DNA Molecules**: Any recipient performing research involving recombinant DNA molecules and/or organisms and viruses containing recombinant DNA molecules agrees, by acceptance of this award, to comply with the National Institutes of Health "Guidelines for Research Involving Recombinant DNA Molecules," July 5, 1994 (59 FR 34496) as amended, or such later revision of those guidelines as may be published in the Federal Register.

12) **Restrictions on Printing**:

Unless otherwise authorized in writing by the AAO, reports, data, or other written material produced using funds provided by this award and submitted hereunder shall be reproduced only by duplicating processes and shall not exceed 5,000 single page reports or a total of 25,000 pages of a multiple page report. These restrictions do not preclude the writing, editing, and preparation of manuscript or reproducible copy of related illustrative materials if required as a part of this award, or incidental printing such as forms or materials necessary to be used by the recipient to respond to the terms of the award. To satisfy the requirements of the Defense Technical Information Center, at least one copy of

each technical report submitted to the Defense Technical Information Center must be black typing or reproduction of black on white paper or suitable for reproduction by photographic techniques. Reprints of published technical articles are not within the scope of this paragraph.

In accordance with Executive Order 12873, dated October 20, 1993, as amended by Executive Order 12995, dated March 25, 1996, the recipient is encouraged to submit paper documents, such as letters or reports, that are printed/copied double-sided on recycled paper that has at least 30 percent postconsumer material.

13) **Prohibition on Awarding to Entities that Require Certain Internal Confidentiality Agreements**

a) The recipient shall not require employees, contractors, or subrecipients seeking to report fraud, waste, or abuse to sign or comply with internal confidentiality agreements or statements prohibiting or otherwise restricting such employees or contractors from lawfully reporting such waste, fraud, or abuse to a designated investigative or law enforcement representative of a Federal department or agency authorized to receive such information.

b) The recipient must notify its employees, contractors, or subrecipients that the prohibitions and restrictions of any internal confidentiality agreements inconsistent with paragraph (a) of this award provision are no longer in effect.

c) The prohibition in paragraph (a) of this award provision does not contravene requirements applicable to any form issued by a Federal department or agency governing the nondisclosure of classified information.

d) If the Government determines that the recipient is not in compliance with this award provision, it:

1) Will prohibit the recipient's use of any FY 2016 or FY 2015 funds under this award, in accordance with Federal appropriations law; and

2) May pursue other remedies available for the recipient's material failure to comply with award terms and conditions.

Exhibit B
HR0011-16-2-0021

RESEARCH DESCRIPTION DOCUMENT
March 28, 2016

Summary: The objective of this effort is to seek to unlock the potential of indirect light transport events. This effort will focus on a general class of computational imaging systems that are "transport-aware" so that photons can be selectively prevented from contributing to an image based on the actual 3D light path followed.

Descriptions of tasks and deliverables are described below:

Year 1

Task 1 - Thrust A: Theory and Systems for Light Transport Parsing

- Develop mathematical formulation and algorithms for parsing by solving an optimization function that separates the light paths while maximizing energy efficiency.

Subtasks:

1. Low-frequency, high-frequency and light field transport parsing
2. Explore Near Infra-Red imaging for transport parsing
3. Bounce decomposition
4. Fabrication of sensor for two-bucket transport parsing
5. Combine geometry and time-of-flight for parsing.

Objective: To develop the theory of light transport parsing by separating light paths into interesting sub-paths (both direct and indirect) that are useful for understanding both the LOS and non-LOS scenes.

Deliverables: Quarterly reports on performances of light transport parsing and annual prototype demonstrations for parsing.

Task 2: Thrust B: Scene Reconstruction by Light Transport Parsing

- Develop bounce based decomposition to recover 3D structure and material properties of scenes
- Develop reduced model based optimization for Analysis by Synthesis with guarantees for convergence and sampling rates

Objective: Develop methods for reconstruction of both line of sight and non-line of sight scenes using the results obtained in the light transport parsing task (Thrust A).

Subtasks:

1. Reduce models for planar and non-planar transport, diffuse indirect LOS and NLOS scenes
2. 2-, 3-, 4-, bounce models for BRDF estimation
3. Investigate non-linear embeddings for model reduction
4. Reduce models for transient light transport

Deliverables: Quarterly reports on the performances reduced models for scene reconstruction including validation and accuracy estimation for datasets collected.

Year 2

Task 1 - Thrust A: Theory and Systems for Light Transport Parsing

- Develop mathematical formulation and algorithms for parsing by solving an optimization function that separates the light paths while maximizing energy efficiency

Objective: Continue developing the theory of light transport parsing by separating light paths into interesting sub-paths (both direct and indirect) that are useful for understanding both the line-of-sight and non-line-of-sight scenes

Subtasks:

1. Decompose transport paths into long range and near range, specular and diffuse indirect
2. Develop theory of light-field-based transport parsing
3. Investigate energy-efficient two-bucket parsing
4. Iterate on design and fabrication of sensor for two-bucket transport parsing
5. Study recoverability and limitations of each node in the transport parse tree

Deliverables: Quarterly reports on performances of light transport parsing and annual prototype demonstrations.

Task 2: Thrust B: Scene Reconstruction by Light Transport Parsing

- Develop bounce based decomposition to recover 3D structure and material properties of scenes
- Develop reduced model based optimization for Analysis by Synthesis with guarantees for convergence and sampling rates

Objective: Continue developing methods for reconstruction of both line of sight and nonline of sight scenes using the results obtained in the light transport parsing task (Thrust A).

Subtasks:

1. Simultaneous transport parsing and bounce graph based reconstruction
2. Simultaneous transport parsing and reduced model based reconstruction
3. Collect large dataset with different objects for LOS and NLOS scenes
4. Design adaptive imaging with fast reduced model based reconstruction
5. Demonstrate and evaluate LOS/NLOS reconstruction for complex geometries
6. Analyze recoverability of BRDF/BSSRDFs for opaque and translucent objects

Deliverables: Quarterly reports on the performances reduced models for scene reconstruction including validation and accuracy estimation for datasets collected

Milestone Schedule for Year 1

Tasks	Milestones	Timeframe
Thrust A	• Low-frequency, high-frequency transport parsing • Explore Near Infra-Red imaging for transport parsing	3 months from award
Thrust B	• Reduced models for planar and non-planar transport components • Reduced models for diffuse indirect LOS and NLOS • 2-Bounce models for BRDF estimation	3 months from award
Thrust A	• Bounce decomposition (2-, 3-, 4- bounces) • Fabricate PCB-based test platform for 1st-generation CMOS sensors • Derive energy efficient metrics for low/high-frequency, bounce parsing	6 months from award
Thrust B	• Reduced models for bounce decompositions • Investigate non-linear embeddings instead of linear reduced models • Shape estimation from 3-bounce and higher-order bounces	6 months from award
Thrust A	• Two-bucket transport parsing with 1st-gen CMOS sensor • Derive energy efficient coding for light field parsing • Test time-of-flight and epipolar imaging on the same 1st-gen CMOS sensor • Implement parsing using 1st-gen CMOS sensor	9 months from award
Thrust B	• Reduced models for light field-based parsing • Optimality guarantees for reduced model based inverse rendering • Evaluate reconstruction accuracy and ambiguities of LOS and NLOS scenes	9 months from award
Thrust A	• Develop general theory of two-bucket transport parsing • Combine time-of-flight and epipolar constraints for better path selectivity • Build prototype of energy efficient episcan ToF sensor for transport parsing • Submit 2nd-gen sensor design to CMOS fabrication facility	12 months from award
Thrust B	• Complete taxonomy of shape/reflectance estimation from multi-bounce graphs • Build reduced models for transient transport components • Demonstrate LOS/NLOS reconstruction for simple shapes using prototypes	12 months from award

Milestone Schedule for Year 2

Tasks	Milestones	Timeframe
Thrust A	• Decompose transport paths into long range and near range • Investigate energy-efficient two-bucket parsing • Develop theory of light-field-based transport parsing • Test deeper transport parsing nodes with two-bucket 1st-gen CMOS sensor	15 months from award
Thrust B	• Simultaneous transport parsing and bounce graph based reconstruction • Simultaneous transport parsing and reduced model based reconstruction	15 months from award
Thrust A	• Decompose paths into specular and diffuse indirect • Decompose paths into translucent indirect, diffuse indirect, specular indirect • Build light-field transport parsing prototype using 1st-gen sensor • Initial testing of 2nd-gen CMOS sensor	18 months from award
Thrust B	• Collect large dataset with different objects for LOS and NLOS • Evaluate feasibility of different multi-modal transport prototypes for the dataset • Investigate fundamental limitations of each transport node for reconstruction	18 months from award
Thrust A	• Iterate on the two-bucket and ToF combination design for CMOS • Integrate 2nd-gen sensor into our time-of-flight/light-field-based prototypes • Finalize design of 3rd-gen programmable CMOS sensors	21 months from award
Thrust B	• Design adaptive imaging with fast reduced model based reconstruction • Analyze recoverability of BRDF/BSSRDFs for opaque and translucent objects	21 months from award
Thrust A and B	• Demonstrate and evaluate LOS/NLOS reconstruction for complex geometries • Study recoverability and limitations of each node in the transport parse tree • Test energy efficiencies of the prototypes in the presence of ambient light • Study accuracy tradeoffs with acquisition times	24 months from award

Additional Deliverables:

1. Quarterly reports detailing the progress made in the previous quarter including: theoretical foundations, algorithms for estimation, experimental results, evaluation of limitations and the next steps
2. Datasets distributed in an open platform
3. Annual demonstrations of the prototype systems
4. Exchanging ideas at forums with researchers
5. Publish the results in highly competitive conferences and journals.

Agreement No.: HR0011-16-2-0021
Purchase Request No.: HR0011622709
Modification No.: P00001
Effective Date: May 16, 2016
DARPA's CFDA Number: 12.910
DODDAC: HR0011

Issued by: Defense Advanced Research Projects Agency (DARPA)
Contracts Management Office (CMO)
675 North Randolph Street
Arlington, VA 22203-2114
(Attn: Michael S. Mutty, 571-218-4588, michael.mutty@darpa.mil)

Recipient: Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA, 15213-3815
(Attn : (b)(4); (b)(6) [redacted]

Recipient Identification Numbers/Codes:

DUNS: (b)(4) [redacted]
CAGE:
TIN:

Total Cooperative Agreement Amount: $998,910.00

Accounting and Appropriation Data:

SUBCLIN	ACRN
0001/01	AA

FUND CITE
012199 097 0400 000 N 20162017 D 1320 DRVLDD 2016.MS-01.CORE.A DARPA 255

AMOUNT
$484,707.00

Payment Office Information:
DFAS IN VP DAI DARPA
8899 East 56th Street
Indianapolis, IN 46249-1500
DODAAC: HQ0685

[AWARD SUBJECT TO ELECTRONIC FUNDS TRANSFER (EFT) REQUIREMENT]
Authority: This Agreement is issued pursuant to the authority of 10 U.S.C. § 2358, as amended.

COOPERATIVE AGREEMENT SCHEDULE

Add to the Purpose as follows:

1. Purpose: The purpose of this modification is to provide an increment of funds in the amount of $484,707.00 to fully fund the Cooperative Agreement.

Revise Cooperative Agreement Funding as follows:

8. Cooperative Agreement Funding: This Cooperative Agreement is fully funded in the amount of $998,910.00. The Government's obligation to make payments to the Recipient is limited to only those funds obligated by this Cooperative Agreement or by modification to this Cooperative Agreement. The Cooperative Agreement Awardee shall notify the AAO in writing promptly whenever the total Cooperative Agreement amount is expected to exceed the needs of the Cooperative Agreement Awardee for the project period by more than 5% of the award. This notification shall not be required if an application for additional funding is submitted for a continuation award.

FOR THE UNITED STATES OF AMERICA,
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

(b)(6) [redacted]

5/16/2016

MICHAEL S. MUTTY
Agreements Officer
Contracts Management Office

Date